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Sukumar Patil (✉ sukumarp@centumelectronics.com)

Power Electronics <https://orcid.org/0000-0003-0265-799X>

Bhanuprakash CV

Centum Electronics Ltd

Bhoopendrakumar Singh

Centum Electronics Ltd

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Multioutput Flyback DC-DC Converter for MIL Applications

Sukumar Patil^{1*} · Bhanuprakash CV² · Bhoopendrakumar Singh³

1,2,3 Power Electronics, Centum Electronics Ltd, Bengaluru, India
 * Sukumar Patil
 sukumarp@centumelectronics.com

Abstract

This paperwork explains the design and development of isolated triple output dc-dc converter for military applications. Converter has designed with flyback topology with opto-coupler based feedback for regulated main output and regulators are used to provide another two outputs. It is realized with switching frequency of 190KHz (internal free run frequency) and can be able to operate up to 210KHz with external synchronization. LTM46xx micro-modules are used as buck regulators to provide required lower output voltages. Current mode pulse width modulation controller IC is used to drive the MOSFET switch. It has following features like inbuilt EMI filter, external inhibit function, external synchronization capability, input under voltage and over voltage protection, primary side over current, output over current and short circuit protection. Converter is designed to operate for wide input range from 18V to 36V with efficiency of more than 75% in full load conditions.

Keywords Flyback dc-dc converter · Triple outputs · Micro-module regulators · Various features · Higher efficiency

1 Introduction

Topology selection is the major activity while designing any dc-dc converter power supply. Converter topology can be selected based on power handling capability and efficiency. Optimized topology with less component count to meet smaller size is important. Hence flyback converter becomes the first choice. It has various advantages over other topologies as it does not require output inductor for operation [1].

Flyback converter main transformer acts as inductor which stores the energy during on period and transfers the stored energy to the secondary side during off period [1]. Converter is designed to develop one main regulated secondary voltage, and which is fed to buck regulators further to produce required another two output voltages. LTM46xx micro-modules are used as buck regulators to

provide required lower output voltages, which can operate for input voltage of 2.2V to 5.5V and has efficiency of more than 95% [2].

2 Specification and operation of dc-dc converter

Below table 1 shows the specification of proposed dc-dc converter. Fig. 1 shows the operational block diagram of dc-dc converter.

Table 1 Electrical specification of dc-dc converter

Input voltage	: 18Vdc~36Vdc
Output voltages	: 5V/5A (main), 1.24V/4A, 1.5V/3A
Switching frequency	: 190KHz
Output power	: 35W
Line & Load regulation (%)	: $\leq 1\%$ for main output : $\leq 3\%$ for lower voltage output
Ripple (mV)	: 50mV (Max 1%)
Efficiency	: $> 75\%$ (Typical)
Operating temperature	: -55°C to $+85^{\circ}\text{C}$ (Base plate)
Storage temperature	: -55°C to $+125^{\circ}\text{C}$

2.1 Brief operation of converter

The operational block diagram of dc-dc converter is shown in Fig.1. Input voltage is supplied to flyback transformer through EMI filter. When switch is ON, transformer will store the energy and during OFF period, stored energy will transfer to secondary side. It has three output voltages. Main output (5V/5A) is regulated output and its voltage is taken as feedback to control the duty cycle and regulate the output voltage. This main output is fed to post micro modules to generate 1.24V & 1.5V outputs.

Fig. 1 Block diagram of proposed dc-dc converter

LTM46xx devices are used as regulators which has higher efficiency of more than 95% [2].

Opto-coupler based isolated feedback method [3] is used for the isolation between input and output stages. Sensed feedback voltage will be given to error amplifier of PWM IC [4] and output of EA will further be compared with ramp voltage which gives required duty to generate output voltage. Current mode control is implemented for accurate and faster loop stability. Primary inductor current through switch is sensed by small value resistor which generates ramp voltage.

Reverse polarity protection & Input Overvoltage Protection are mosfet based circuits which placed in input return path as shown in Fig.2. This circuit protects the converter against input over voltage and negative voltages.

Fig. 2 Reverse polarity protection and over voltage protection

Short circuit and other protection circuits like under voltage protection and over temperature protections are implemented for safety of the converter.

Converter has input under-voltage protection where converter goes in shutdown mode if input voltage goes below 16.5V and regain when input increases to 17.2V. Fig. 2a. Shows the operation of UVP protection and same is implemented and tested in hardware.

Short circuit and overload protection are implemented as shown in fig. 2b. Whenever short and overload condition

occurs on output side (120% of output current), converter will go in hiccup protection mode. Transformer inductor current is sensed through small resistance value (R_{sense}), averaged value is then compared with constant reference. R_{sense} can be selected by considering the power dissipation across it.

Fig. 2a Under voltage protection circuit

$R1$ and $R2$ can be selected by equation (1)

$$V_{th} = \frac{V_{UV} \times R2}{R1 + R2} \quad (1)$$

Where,

V_{UV} is Input under voltage level

Overtemperature protection is implemented by using comparator. Operational circuit is shown in fig. 2c. Thermistor resistance value will change as temperature changes. Initially at room temperature thermistor resistance will be 10K and gradually decreases to 833 Ω @ 105°C. Hence as shown in fig. 2c $R1$ value can be calculated in such way that at ambient condition V_{th} voltage will be much higher than V_{ref} voltage. When V_{th} voltage goes less than V_{ref} voltage, circuit gives high output to shutdown circuit and turn-off the converter. Temperature limit can be set by referring Resistance vs temperature curve from thermistor datasheet [5].

Fig. 2b Over current and short circuit protection circuit

Fig. 2c Over temperature protection circuit

The LTM4608A [2] is a complete 8A switch mode DC/DC power supply which includes the switching controller, power FETs, inductor, and all support components inside the package. It has operating input voltage range of 2.7V to 5.5V. Hence the main output is fed to this buck micro-modules to regulate 1.24V and 1.5V outputs. Outputs can be set by a single external resistor. Operational circuit is shown in fig. 2d.

Fig. 2d Buck micro-module circuit

3 Design calculations and component selection

As known, design of magnetic coils, selection of proper semiconductor devices plays important role in performance of all the dc-dc converter. Major design considerations are explained below.

3.1 Transformer design

Transformer is key part and plays very important role in any kind of dc-dc converter. Hence proper selection of core turns ratio, operating flux density, wire gauge of conductors become very crucial.

The power handling capacity of a transformer core can be determined by its area (WaAc) product method [6]. Area product (Ap) is given as the product of the core cross section (Ac) and window area (Wa).

$$Ap (WaAc) = \frac{L_p \times I_{pp} \times A_{p0}}{K_w \times J \times 10^{-6} \times B_m} (mm^4) \quad (2)$$

Where,

$$A_{p0} = I_{prms} + (I_{srms1} \times Tratio1) + (I_{srms2} \times Tratio2) + (I_{srms3} \times Tratio3)$$

$$Tratio_n = \frac{V_{out_n} \times V_{fd_n}}{V_{in(min)}} \times \frac{1-D}{D}$$

L_p = Primary inductance (H) I_{pp} = Primary peak current (A)
 K_w = Window factor (0.4~0.5) J = Current density (A/mm²)
 B_m = Flux density (Tesla)
 V_{fd} = Secondary diode forward voltage drop
 D = Duty

Selected core must have area product greater than the calculated A_p .

Primary (N_p) and secondary turns (N_s) can be calculated by equations (3)-(4)

$$N_p = \frac{L_{pp} \times I_{pp}}{B_m \times A_c \times 10^{-6}} \quad (3)$$

$$N_{s_n} = Tratio_n \times N_p \quad (4)$$

After finalizing the number of turns, calculate the required wire gauge to carry the flowing current in respective windings. Use multiple wires to reduce the losses and heat.

Calculate the copper and core losses to know the temperature raise and should not reach beyond the maximum operating temperature.

3.2 Output capacitor selection

Output capacitor value can be calculated by using equations (5)-(6).

$$C_{out} = \frac{I_{out} \times (1 - D_{min}) \times T_s}{\Delta V} \quad (5)$$

$$I_{s_reflected} = \left(\frac{1-D}{D} \right) \times \frac{I_{pp}}{\frac{N_s}{N_p}} \quad (6)$$

Where,

T_s = Switching period

ΔV = Ripple voltage

I_{pp} = Primary peak current

$I_{s_reflected}$ = Reflected current on secondary side

ESR of capacitor is the key aspects of ripple voltage. Hence low ESR capacitors should be chosen as per requirement. In most of the power supplies ceramic capacitor will be chosen.

Required ESR to meet ripple voltage can be calculated using equation (7)

$$ESR = \frac{\Delta V}{I_{s_reflected}} \quad (7)$$

Multiple number of capacitors can be selected to meet required ESR.

3.3 Primary Mosfet selection

Main critical part of any dc-dc converter is selection of mosfet switch. It consists various losses like conduction loss, gate charge loss, switching losses and Coss losses.

Hence mosfet losses can be calculated by using equation (8),

$$P = (R_{DS(on)} \times I_{P(rms)}^2) + \left(\frac{1}{2} \times C_{OSS} \times V_{DS}^2 \times F_{SW}\right) + (Q_g \times V_G \times F_{SW}) + \left(\frac{1}{2} \times V_{DS} \times I_D \times (T_{rise} + T_{fall}) \times F_{SW}\right) \quad (8)$$

Where,

$R_{DS(on)}$ = Drain to source resistance

Q_g = Gate charge

T_{rise} = Rise time

T_{fall} = Fall time

C_{oss} = Total output capacitance

Suitable mosfet can be chosen based on losses, drain to source voltage, and drain current. In higher losses, use the proper snubber to reduce the stresses on switch.

3.4 Output diode selection

The forward voltage drops (VFD) of diode directly impact on diode loss and it becomes critical in high current load applications.

Diode loss can be selected by using equation (9)-(11),

$$P_{diode} = V_{fd} \times I_{out} \quad (9)$$

$$I_{s_reflected} = \left(\frac{1-D}{D}\right) \times \frac{I_{pp}}{\frac{N_s}{N_p}} \quad (10)$$

$$V_{s_reflected} = (V_{out} + V_D) + \left(\frac{N_s}{N_p} \times V_{in_max}\right) \quad (11)$$

Where,

V_{fd} = Diode forward voltage drop

$V_{s_reflected}$ = Reflected voltage on secondary side

Hence suitable diode can be chosen based on losses and output current and voltage stress ratings. Schottky diodes are preferred on output side.

4 Quality of components and analysis

Component grade for the military and defense application is critical as converter will expose to harsh environment. Hence MIL qualified components to be selected. Industrial components with extended temperature (-55°C to +155°C) can be selected in case of cost constraints.

All components should be well derated as per required MIL-STD to reduce the stress on components and increasing the life.

Following analysis like power dissipation, derating analysis, FMECA analysis, reliability analysis to be considered while designing rugged and reliable power supplies for military applications.

Power dissipation analysis is required to know the dissipation of each component and thermal raise.

Derating analysis is required to reduce the stress level of components and increasing the working life of components.

FMECA is failure mode analysis which is required to analyze the failure effect of each component on power supply performance and end system.

Reliability analysis will tell the life of product. Higher the reliability longer the life. For this reliability is done as per MIL-STD-217F handbook [7].

5 Practical results and waveforms

Proposed converter is designed, implemented, and tested under all the required tests conditions. Converter meeting all the electrical specifications under temperature ranges from -55°C to +85°C. Converter will comply with MIL-STD461E [8], MIL-STD810D [9], MIL-STD1275 and MIL-STD704A&D [10] tests requirements.

Converter can deliver 35W power output with higher efficiency of more than 75% over an entire input voltage ranges from 18V to 36V at full-load condition.

5.1 Electrical performance results of converter

Proposed converter output voltage regulation readings,

ripple voltage readings and efficiency of converter is tabulated in below Table 2, Table 3 & Table 4, respectively.

Table 2 Output voltage regulation

Output Voltage & current	Output regulation ranges (V)	No-load	Vin 18V	Vin 28V	Vin 36V
			Full load	Full load	Full load
5V_5A	4.95-5.05	4.99	4.98	4.99	4.98
1.24V_4A	1.19-1.29	1.25	1.22	1.23	1.22
1.5V_3A	1.46-1.54	1.51	1.48	1.49	1.48

Table 3 Output ripple voltage readings

Output Voltage & current	Vin 18V	Vin 28V	Vin 36V
	Full load (mV)	Full load (mV)	Full load (mV)
5V_5A	34	20.8	24
1.24V_4A	12.8	9.6	11.2
1.5V_3A	16	13.6	15.2

Table 4 Efficiency of proposed converter

Input Voltage (V)	Efficiency (%)
18	76.02
28	76.81
36	77.21

5.2 Mosfet gate and drain voltage waveforms

Fig. 3 shows the mosfet gate-source and drain voltage waveforms measured at Vin=28V at full-load condition.

Fig. 3 Mosfet Vds and Vgs voltage waveforms at Vin=28V, at full-load condition, Ch-1:Vgs (12V), Ch2-Vds (58.4V)

5.3 Output diode stress voltage waveforms

Fig. 4 shows the output diode stress voltage waveforms measured at Vin=28V at full-load condition.

Fig. 4 Output diode stress voltage waveform at Vin=28V, at full-load condition, Ch-1:Vgs (12V), Ch2-Vdiode (12.8V)

5.4 EMI-EMC test result waveforms

Fig. 5 and Fig. 6 shows the EMI-EMC CE102 and RE102 test result waveforms measured at Vin=28V at full-load condition, respectively.

Fig. 5a CE102 test result waveform at 28V and on high line

Fig. 5b CE102 test set-up

Fig. 6 RE102 test result waveform at 28V with vertical polarization

5 Conclusion

It is always challenging for designer to design rugged and higher reliable dc-dc converter for military and defense applications.

Because such designs require less component count, proper thermal design to dissipate heat, good layout design to avoid noise interference.

These are achieved by selecting the optimize the topology and selection of circuits which requires minimum components. Using of multiple layers for thermal and mounting the higher dissipating parts on chassis for the thermal solution. Good layout is achieved by separating the EMI section and power section. In power section, again signal tracks are routed away from power tracks and sensitive signal tracks in feedback loop section are routed with guard rings.

The proposed converter is tested for wide input voltage range from 18V to 36V under all load conditions from -55°C to +85°C (base plate).

Converter has efficiency of more than 75% in all conditions and complied to MIL-STD461E.

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Figures

Fig. 1 Block diagram of proposed dc-dc converter

Figure 1

Block diagram of proposed dc-dc converter

Fig. 2 Reverse polarity protection and over voltage protection

Fig. 2d Buck micro-module circuit

Figure 2

Fig. 2b Over current and short circuit protection circuit

Fig. 2c Over temperature protection circuit

Reverse polarity protection and over voltage protection. 2a Under voltage protection circuit. 2b Over current and short circuit protection circuit. 2c Over temperature protection circuit. 2d. Buck micro-module circuit

Fig. 3 Mosfet Vds and Vgs voltage waveforms at Vin=28V, at full-load condition, Ch-1:Vgs (12V), Ch2-Vds (58.4V)

Figure 3

Mosfet Vds and Vgs voltage waveforms at Vin=28V, at full-load condition, Ch-1:Vgs (12V), Ch2-Vds (58.4V)

Fig. 4 Output diode stress voltage waveform at Vin=28V, at full-load condition, Ch-1:Vgs (12V), Ch2-Vdiode (12.8V)

Figure 4

Output diode stress voltage waveform at $V_{in}=28V$, at fullload condition, Ch-1:Vgs (12V), Ch2-Vdiode (12.8V)

Fig. 5a CE102 test result waveform at 28V and on high line

Fig. 5b CE102 test set-up

Figure 5

5a CE102 test result waveform at 28V and on high line. 5b CE102 test set-up

Fig. 6 RE102 test result waveform at 28V with vertical polarization

Figure 6

RE102 test result waveform at 28V with vertical polarization