Design and Implementation of 75W Mag-Amp Controlled Forward Converter for Communication System

Kalpana N[1], Shubha Kulkarni[2], B K Singh[3], Santosh B L[4], Prakash G[5]

[1] M.Tech, Dept of EEE, DSCE, kalpana.nmurthy@gmail.com
[2] Associate Professor, Dept of EEE, DSCE, shubha-eee@dayanandasagar.edu
[5] Engineer, Centum Electronics Ltd, prakashg@centumelectrnics.com

Abstract.

The application of DC-DC converter is booming in the field of power electronics design applications in this era. This paper elaborates the usage of forward converter with reset winding. The Magnetic-amplifiers(Mag-Amp) are used as a post regulator for the dual output to maintain the right output voltage and to maintain lesser ripple. Voltage feed forward has been implemented to improve the converter performance against fast changing input voltage. It is used to comply this converter for military standard. Basic design procedure and all the specifications are covered in this paper. The paper is focused on design and hardware implementation of voltage mode controlled dual output converter. The proposed converter delivers output of 6V/12A (output1) and 6V/0.5A (output2) and operates at switching frequency of 140 kHz. Voltage feed forward technique is implemented using UC2525 Pulse Width Modulation controlled circuit (PWM IC). It is aimed to achieve converter efficiency greater than 68%.
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Keywords: DC-DC converter, Magnetic Amplifier, Voltage feed forward control, Forward converter, LCD Snubber, UC2525 PWM controller.

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1. INTRODUCTION

In SMPS applications, forward converter topology has been used for low power applications ie.,100W to 200W. It's use can be found in military, aero-space, renewable energy, space application, automotive industries [1]. It is important to have high reliability than the efficiency for space missions. Single switch forward converter is implemented in this paper. It operates for an input DC voltage of 24V- 42.5V giving a dual output voltage of 6V/12A and 6V/0.5A. An inrush current limiter circuit is being placed at the input side to protect converter from high magnitude current when power supply is plugged in. The converter has a built in EMI filter to mitigate noise which is reaching converter as well as coming out of converter. Voltage feed-forward control technique is used to achieve good line regulation which gives an instantaneous response to the changes in the input voltage thereby adjusting the duty cycle. The voltage spikes on MOSFET are caused due to leakage inductance. An LCD (Inductor, Capacitor, Diode) snubber is used to protect the circuit against spikes [2].

2. SPECIFICATIONS AND BLOCK DIAGRAM

Table I Specification of the forward converter

Parameter	Specification
Input voltage	24V(min),36V(nom),42.5V(max)
Outputs	6V/12A, 6V/0.5A
Efficiency	$\geq$ 68%
Line regulation	<1%
Load regulation	<2%
Operating frequency	140 ± 5kHz
Ripple Voltage	<30mV$_{p-p}$ (5%)
D_{max}	35%
D_{min}	20%

The Fig 1 represents the basic circuit diagram of the dc-dc converter and Fig 2 shows the complete block diagram of the mag-amp controlled forward converter, which includes EMI filter to mitigate noise coming from the converter as well as to the converter. Inrush current limiter circuit, limits the input current on application of ON command with 100% load to less than the twice of input current. Current sense circuit protects converter from over current or short circuit current. The duty cycle of the switch is controlled using voltage feed forward technique, Start-up circuit provides power supply to the IC's. PWM controller turns ON and initiates GATE pulses at switching frequency of 145±5 kHz.to primary side of MOSFET. The rectifier circuit and output filters are used to get the rectified output voltage with ripple less than 30mV$_{p-p}$. To achieve the load regulation less than 2% mag-amps are used as post regulators. Over voltage protection circuit does not allow output voltage to exceed 120% of the actual output.

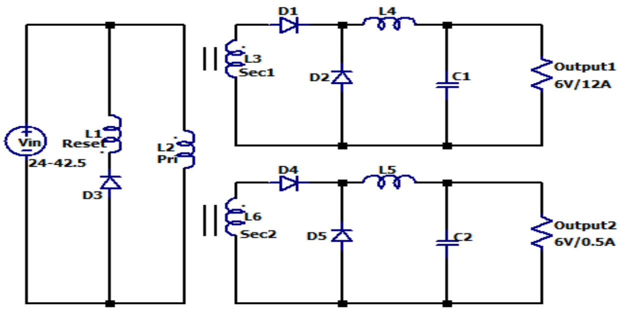


Fig 1. Basic Circuit of the forward converter

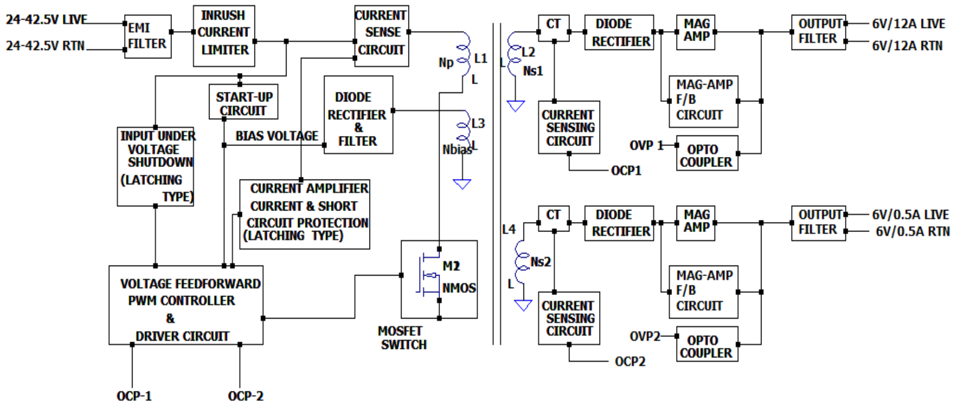


Fig 2. Block Diagram of the forward converter

3. DESIGN PROCEDURE

The above specifications are used in designing prototype model of the converter. In this section a) design of transformer, b) criteria for MOSFET selection and snubber design, d) mag-amp design and e) output filter design are explained

3.1. Voltage Feed Forward

Variations in input voltage affect the overall performance of the circuit through duty cycle variations. In order to avoid that there must be a loop which corrects the duty cycle, so that even though there is a change in the input voltage the output voltage is not affected [3]-[4]. The voltage feed forward mode of PWM control is used which adjusts the duty ratio according to the changes in the input voltage. This type of feed forward technique uses RC network to generate saw tooth waveform using input voltage which is shown in the Fig 2 & 3. As the input goes high or doubles, the slope of the comparator will also doubles which causes the duty cycle will immediately be halved. This type of duty cycle correction is very much important for circuit in order to wait for an error amplifier to detect the error in the output voltage.

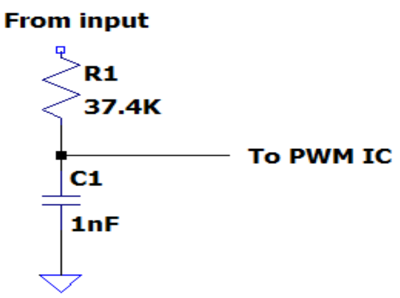


Fig.2 RC network for saw tooth wave generation.

Fig.3 Saw tooth wave generated using RC network

3.2. *Transformer Design*

For designing transformer area product must be calculated. Usually, a core is selected based on the area product method and it's calculated using equation (1).[4]-[5]

In a forward converter area product is given by:

$$A_P = \frac{\sqrt{D}\,.P_{out}.\left(1+\frac{1}{Eff}\right)}{K_w\,.\,J.\,10^{-6}\,B_m\,.Fsw} \quad (1)$$

A_p = Area product of the core (mm^4); K_w = Window factor ; Pout = Output power (W)
J = Current density (A/mm^2): D_{max} = Maximum Duty cycle; B_m = Maximum flux density (T) ; F_{sw} = Switching frequency (Hz).

For ferrite core Kw = 0.35, Bm= 0.12T, J=6A/mm^2

$$A_p = \frac{\sqrt{0.4}.75.(1+\frac{1}{0.65})}{0.3.6.10^{-6}\,.0.12.140.10^{3.}} = 3378.67\ mm^4$$

Referring to the ferrite core catalogue, an appropriate core is selected which has area product greater than the calculated value and better power handling capacity at converter operating frequency. Therefore, the selected POT core is **OR43019UG** which is having an **A_L=6680nH/1000Turns**.

3.3. *MOSFET Selection and Snubber Design*

Parameters to be considered for selection of MOSFET are drain to source voltage(V_{DS}), gate to source voltage(V_{GSth}) required to turn it on, continuous drain current(I_{Dmax}), drain to source ON resistance (R_{DS}(on)), input capacitances(C_{iss}) and output capacitances(C_{oss}). The stress on the MOSFET is calculated using equation (2)

$$V_{peak\text{-}MOSFET} = V_{in\text{-}max}\left(1+\frac{Npri}{Nreset}\right) \quad (2)$$

IRHM57260 is selected which has V_{DS} = 200V, $R_{DS\ (on)}$= 49mΩ, I_{Dmax} =35A and $V_{GS(th)}$=2V.

Leakage inductance and resistance causes spikes in voltage and current. This introduces electrical stress on the switching device. So therefore, an LCD snubber is designed to protect switch against these spikes. It consists of two diodes, inductor and capacitor. Based on area product calculation, the core is selected for inductor [5].

$$A_P = \frac{Lsnubber * Iout^2 * (1+\frac{K}{2})}{Kw * Bm * J * 10^{-6}} \quad (3)$$

Selected core is **C055291A2** with **$N_{snubber}$ = 7T**.

3.4. *Mag-amp Design*

Mag-amp is a controlled switch which uses an inductive element [5]. It has a square BH curve characteristic. Basically, it operates in two different modes they are saturated and unsaturated. When it operates in a saturated mode, at that time leakage impedance will be less, producing current to flow through it with less or no voltage drop. But when it operates in unsaturated mode, core makes coil to operate as a high inductance, capable of supporting high voltage with minimum or zero current flow. One of the significances of mag-amp is that load current doesn't determine the reset, but the reset is determined by the core and number of turns as mag-amp is inductive element.

There are additional requirements for selecting the core material, they are [6]

- Regulator output voltage.
- Maximum output current,
- Input voltage waveform including limits for both voltage amplitude and pulse width
- The maximum volt-seconds called the "withstand Area"

The core size is decided by area product method as

$$A_p = \frac{Ax*A*10^8}{\Delta B*K} \text{ cm}^4 \qquad (4)$$

A_x = Wire Area (One Conductor) (mm^2); ΔB = Flux excursion (T)

K= Fill factor ; A= Required withstand area (V-sec)

Selected core is **P/N 6-L2016-W763, square loop core.**

The purpose of designing a control loop is to provide good regulation of the output voltage, not only from a DC standpoint, but in the transient case as well.

3.5. Output filter Design

An output filter basically consists of Inductor (L) as well as Capacitor (C). By assuming optimum ripple values for inductor current and output voltage for L & C respectively we can design the output filter [4].

$$L = \frac{Vo*(1-Dmin)*Ts}{\Delta iL} \text{ H} \qquad (5)$$

$$C = \frac{1-Dmin}{8*L*Fsw^2*\Delta Vo} \text{ F} \qquad (6)$$

Therefore,

L1 = $8.1*10^{-6}$ H; C1 = $846*10^{-6}$ for the filter elements of 6V/12A &

L2= $18*10^{-6}$ H; C2= $376*10^{-6}$F for the filter elements of 6V/0.5A.

4. PRACTICAL ASPECTS AND TEST RESULTS

The Fig 4 & 5 shows top view and experimental set up of the forward converter. The converter is powered up using DC voltage source and output is connected to an electronic load which measures the output voltage and load current. To measure ripple in the outputs a digital storage oscilloscope(DSO) is connected.

Fig 4 Top view of the converter

Fig 5 Overall hardware setup of the converter module

Test results of the proposed forward converter are shown in Table I, Table II, Table III, Table IV and Table V.

Table I .Input and output parameter measurement at full load (100%)

Input Voltages(V)	**Input Current(A)**	**Output parameters**		**Ripple Voltage (mVp-p)**	
		O/P-1 (6V/12A)	O/P-2 (6V/0.5A)	O/P-1 (6V/12A)	O/P-2 (6V/0.5A)
24	4.498	5.974	6.029	12.4	6
36	3.001	5.984	6.031	14.4	6
42.5	2.567	5.987	6.027	14	6

Table II. Output parameter measurement at min load (10%)

Input Voltages(V)	**Output parameters**		**Ripple Voltage (mVp-p)**	
	O/P-1 (6V/1.2A)	O/P-2 (6V/0.05A)	O/P-1 (6V/1.2A)	O/P-2 (6V/0.05A)
24	5.999	6.03	9.6	4
36	5.998	6.032	10.4	3.6
42.5	5.998	6.031	10.8	4

Table III. Efficiency at different input voltages are shown.

Input Voltage (V)	**Output Power (W)**	**Input Power (W)**	**Efficiency (%)**
24V	74.7025	107.952	69.19
36V	74.8235	108.036	68.98
42.5	74.8575	109.097	68.61

Table IV. Shows line regulation at max and min load condition

Load	**Line Regulation (%)**	
	6V/12	6V/0.5A
100%	0.0021	-0.0033
10%	-0.0001	0.0001

Table V. Shows load regulation at different input voltages

V_{in} (V)	**Load Regulation (%)**	
	6V/12A	6V/0.5A
24	0.234	0.017
36	0.084	0.033
42.5	0.017	0.033

5. WAVEFORMS

The Fig 5 shows inrush current waveform at an input voltage of 42.5V. The maximum inrush current is 4.24A, which lasts for duration of 5.8msec and the time taken to reach maximum value is about 2.181msec.

The sudden or sharp changes happening on the power line due to abrupt changes in the load or power supply is known as turn on transient. Fig 6, shows turn on transient waveform at 24V input. It reaches steady state output voltage value of 6V in 4msec.

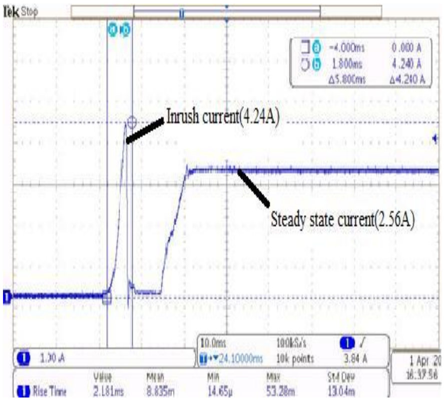


Fig 5 Inrush Current at maximum input voltage (42.5V) and duration of inrush is 5.80msec

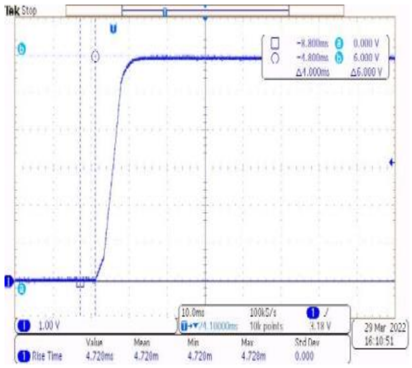


Fig 6 Turn on transient at minimum input voltage (24V)

The ripple voltage waveforms of the dual outputs at 36V input and full load condition is shown in Fig 7. The channel-1 denotes ripple output voltage of 6V/12A and channel-2 denotes ripple output voltage of 6V/0.5A. The measured ripple output voltage is less than the specified value ($30mV_{p-p}$). The ripple in the outputs is reduced using LC filter.

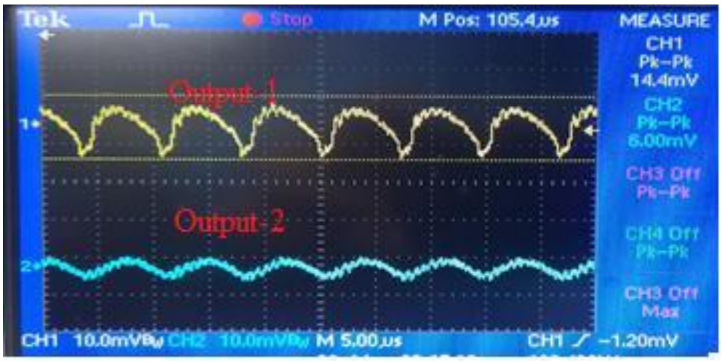
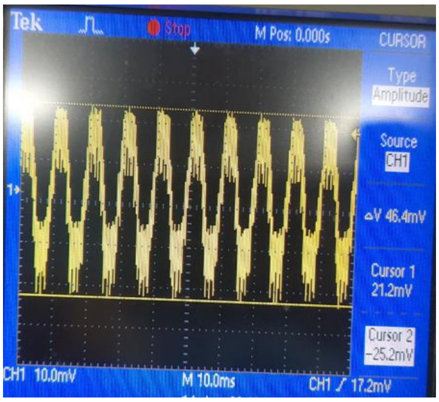


Fig 7 Ripple at full load condition .Output 1-14.4mV; Output 2-6mV

The transient response of the output voltage due to load fluctuation is known as load transient. Fig 8 & Fig 9 shows the load transient response of the outputs 1 and 2. The measured values are less than the specified value of 300mV(5%).



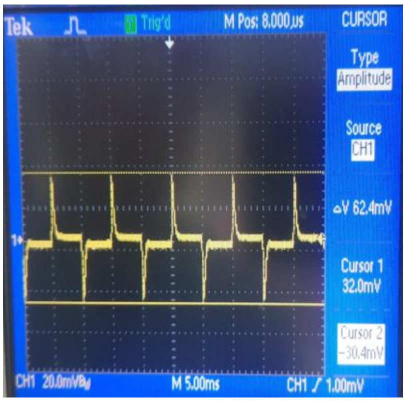


Fig 8 Load Transient of output 1

Overshoot = 21.2mV ; Undershoot = 25.2mV

Fig 9 Load Transient of Output 2

Overshoot = 32.0mV ; Undershoot = 30.4mV

CONCLUSION

The converter is tested satisfactorily for all the specifications mentioned. The mag-amp is used as post regulator, which helps in maintaining good load regulation. The results show that, line regulation within the specification is achieved using voltage feed forward control technique. Feedback circuit on each output regulates the output voltages within the limit. Overall, all the necessary conditions are met and the converter underwent all the tests for the proposed application.

ACKNOWLEDGEMENT

Authors are thankful to the Management, Principal and Vice Principal, Dayananda Sagar College of Engineering and Centum Electronics Ltd. for their continuous support.

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