Design and Realization of a small 10 Watt Forward Converter

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Abstract – **In this paper the straightforward design of a small forward converter is presented. The converter was built and tested through lab measurements. Design steps are described and well documented with measurement results.**

Keywords – **DC/DC converter, forward, efficiency**

I. Introduction

The most frequently used DC/DC converter is a single switch forward converter, especially for telecom use with input voltage range from 18 to 36 or 36 to 72V. It is used in Digital Radio Relay Systems and Radio Base Stations. From few watts to a couple hundred watts, with one or multiple outputs, they need to have high efficiency and high density. Unlike the flyback converter they have two magnetic components: the transformer and the output inductor.

II. Principle of forward converter

The basic forward converter circuit is shown in Fig. 1. During the time when the primary power switch (MOSFET Q) is on, the energy is transferred to the secondary. Diode D1 is forward biased and the current flows through inductor L to the capacitor C and the load. When the power switch turns off, diode D1 is reverse biased and forward biased diode D2 provides freewheeling path for inductor current from input and stored in the transformer. Capacitor C acts as a reservoir and holds the output voltage nearly constant.

III. Design and analysis

The task is to design a 10W forward converter using current mode control IC with careful choice of operating parameters and components. Achieving the efficiency as much as possible near 85% is the primary objective. The footprint size must be smaller than 50x25mm.

First we choose the switching frequency to be around 340 kHz, which is a compromise between the efficiency and size. Knowing that, a good choice of core for the transformer and the inductor is RM4, N49 material from TDK-EPCOS.

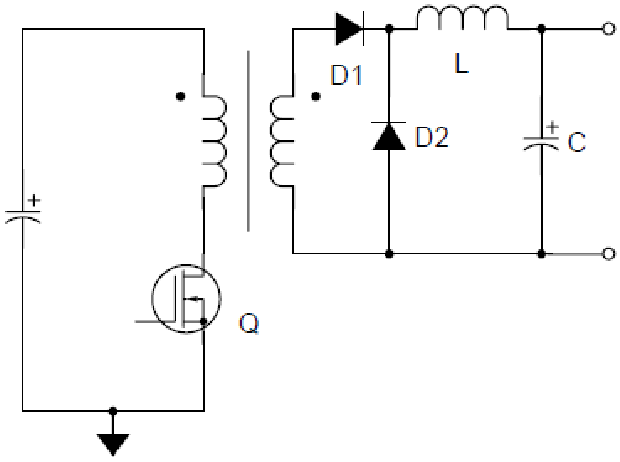

Fig.1. Forward converter

Design specifications are given in Table I.

TABLE I
DESIGN SPECIFICATIONS

		Min	Typ	Max	
Input voltage	V_{IN}	18	24	36	V
Output voltage	V_O		5		V
Output current	I_O	0.1	2		A
Output current limit	I_{OCL}		2.4		A
Full load efficiency	η		85		%
Switching frequency	f_{SW}		340		kHz

The main contributors to power losses are transformer, output inductor, power switch, current sensing and secondary rectifiers.

Starting from design specifications we will now calculate basic parameters for the transformer and output inductor (Table II).

TABLE II
BASIC PARAMETERS

		Max	Typ	Min	
Duty cycle	D	0.43	0.32	0.21	
Number of primary turns	N_P		12		
Number of secondary turns	N_S		8		
Primary RMS current	I_{PRMS}	1.00	0.86	0.70	A
Secondary RMS current	I_{SRMS}	1.31	1.13	0.92	A
Output inductance	L		21		μH
Number of induct. turns	N		14		

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Now it is time to wind the transformer and output inductor. We will use 2 parallel strands of 0.3mm copper wire for the primary and the secondary, in order to minimize copper losses. For the output inductor we will use 3 parallel strands of 0.3mm copper wire.

Knowing specific core losses we can now calculate the losses in both magnetic components (Table III). Total transformer power loss at 24V input voltage is 188mW. This results in approximately 24 °C rise above ambient temperature. The temperature rise on the inductor is 19 °C. Satisfied with results, we will keep the chosen core geometry.

TABLE III
TRANSFORMER AND INDUCTOR LOSSES

		Max	Typ	Min	
Core effect. volume	V_E		0.29		cm^3
Specific core losses	P_V		0.32		W/cm^3
Primary resistance	R_P		66		mΩ
Secondary resistance	R_S		45		mΩ
Core loss	P_{CORE}		93		mW
Primary loss	P_{PRI}	66	49	33	mW
Secondary loss	P_{SEC}	77	57	38	mW
Inductor loss	P_{IND}		157		mW

As the next step we will compute the power losses for power switch IRFR3410 (Table IV).

TABLE IV
IRFR3410 POWER LOSSES

IRFR3410			Typ		
ON resistance	R_{DS}		39		mΩ
Reverse transfer capac.	C_{RSS}		250		pF
Conduction loss	P_{CON}	59	43	29	mW
Switching loss	P_{SW}	78	138	300	mW
Total loss	P_{TOT}	137	181	329	mW

Obviously MOSFET IRFR3410 is a good choice because of the low power losses.

For current sensing we can use a current sense resistor or a current transformer. For simplicity and smaller losses we will use current sense resistor. Power dissipated in current sense resistor is given in Table V.

TABLE V
CURRENT SENSE RESISTOR POWER LOSSES

		Max	Typ	Min	
Current sense resistance	R_{CS}		0.5		Ω
CS resistance loss	P_{CS}	500	370	245	mW

Dissipation of 500mW at low line will reduce efficiency about 4%. For higher efficiency the circuit shown in Fig. 2 will be used. Resistors R_2 and R_3 bias the current sense resistor R_1 reducing a current sense amplitude, so the sense resistor can be three times smaller. As a result we have smaller power loss. The new calculation results are given in Table VI.

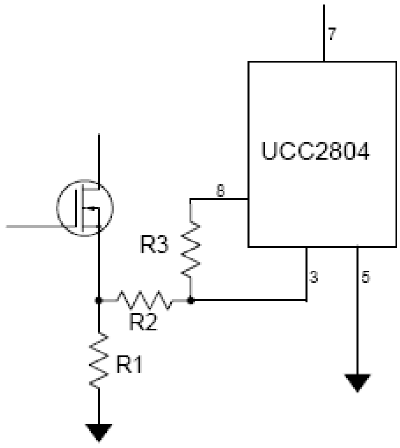

Fig.2. Current sense circuit with bias

TABLE VI
BIASED CURRENT SENSE RESISTOR POWER LOSSES

		Max	Typ	Min	
Current sense resistance	R_{CS}		165		mΩ
CS resistance loss	P_{CS}	165	122	81	mW

With this simple circuit the dissipation is reduced significantly (from 500 to 165mW at low line).

At the end we will calculate the power losses for secondary rectifier – Schottky diode MBRD660CTG (Table VII).

TABLE VII
RECTIFIERS POWER LOSSES

MBRD660CTG		Min	Typ	Max	
Conduction loss	P_{CON}		0.8		W
Switching loss	P_{SW}		0.4		W

Comparing to the other losses it is obvious that the choice of secondary rectifier is critical for the converter efficiency.

IV. REALISATION

DC/DC converter was built on FR-4 substrate with 35μm copper with footprint 50x25mm. The transformer and the output inductor are wounded on through hole coil formers according to calculations. Current sense resistor (with bias) is adopted for primary current sensing.

Using lab power supply 0-60V/3A and resistive load we have measured full load efficiency at various input voltages. The results are given in Table VIII. The efficiency is around 83%, which is not so bad. Simultaneously with efficiency measurements we have recorded the waveforms at the point of interest.

TABLE VIII
EFFICIENCY

			Typ		
Input voltage	V_{IN}	18	24	36	V
Input current	I_{IN}	0.679	0.50	0.340	A
Input power	P_{IN}	12.22	12.00	12.24	W
Efficiency	η	81.82	83.33	81.70	%

The drain waveforms of primary power switch at full load and input voltages of 18, 24 and 36V are given in Figs. 3, 4 and 5 respectively. Drain current waveforms can be seen in Figs. 6 and 7.

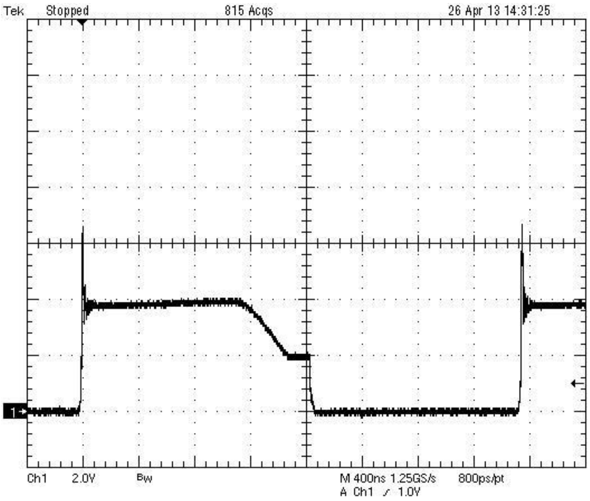

Fig.3. Drain voltage waveform at 18V

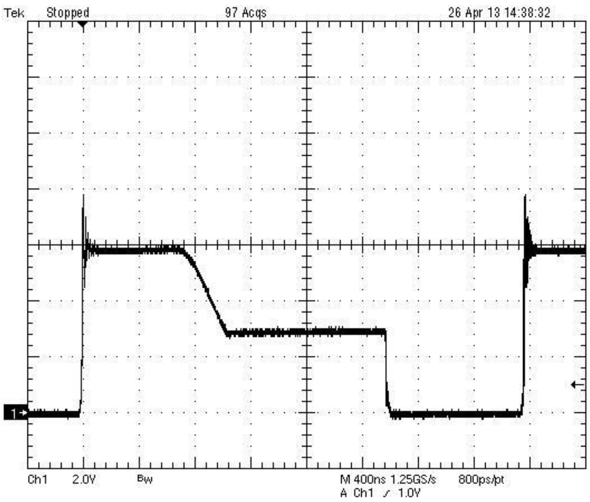

Fig.4. Drain voltage waveform at 24V

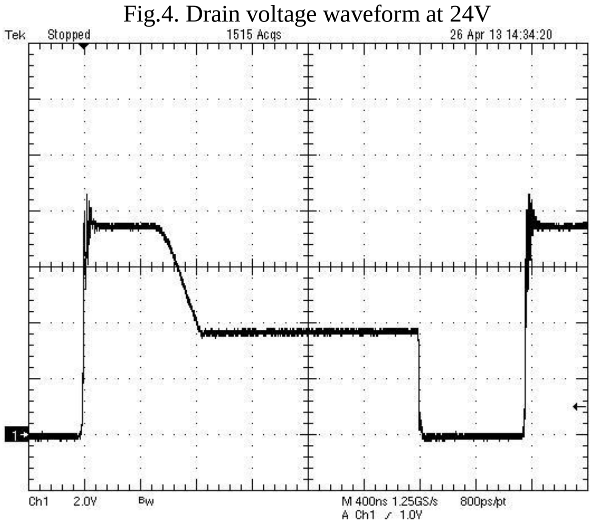

Fig.5. Drain voltage waveform at 36V

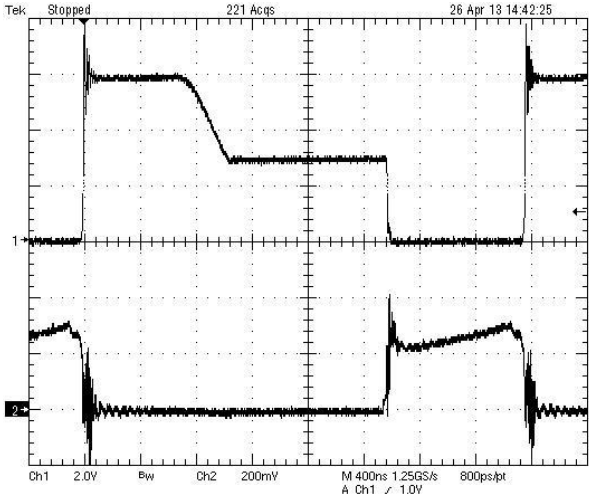

Fig.6. Drain voltage and current waveform at 24V

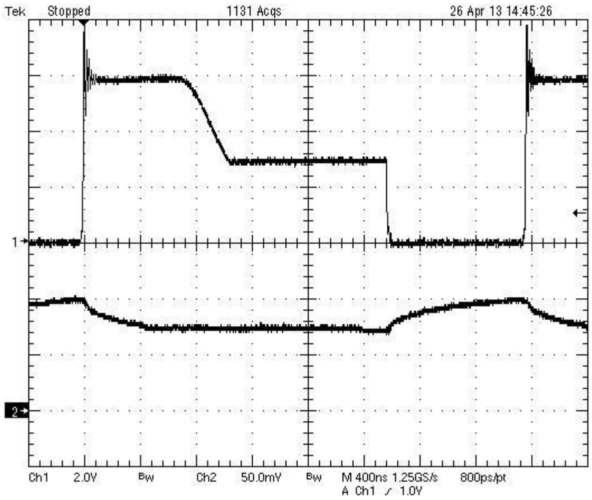

Fig.7. Drain voltage and current waveform (offset) at 24V

At full load, input voltage of 24V and convection cooling we have measured the temperatures of critical components using thermocouple. The results are given in Table IX.

TABLE IX
TEMPERATURE OF CRITICAL COMPONENTS

Temperature (°C)	
Ambient	31
MOSFET	55
Diode	81
Transformer	58
Inductor	57

MOSFET and diode junction temperature can be done more precisely using DMM and stopwatch. DMM must have diode threshold measurement option. First with power off and no load we will measure the forward voltages of FET and diode and ambient temperature.

When the converter reach the steady-state condition, we will turn the power off and remove the load simultaneously starting the stopwatch. At every 20 seconds the forward voltage needs to be measured. The procedure was done for FET and output diode. The results are given in Tables X and XI.

TABLE X
MOSFET VSD

t(s)	20	40	60	80	100	120
V_{sd}(mV)	463	472	480	486	491	495

TABLE XI
DIODE VF

t(s)	20	40	60	80	100	120
V_f(mV)	103	130	142	150	155	158

Using curve-fitting software we can find that at t=0 MOSFET diode voltage is $V_{sd\ HOT}$ = 452mV and output diode voltage $V_{f\ HOT}$ = 79mV. In a cold state we have measured $V_{sd\ COLD}$ = 512mV and $V_{f\ COLD}$ = 184mV. Knowing temperature coefficients for MOSFET diode k_1 = - 2.2 mV/°C and for output diode k_2 = -1.8 mV/°C we can calculate junction temperature for MOSFET using equation

$$T_{JMOSFET} = T_{amb} + \frac{(V_{sdHOT} - V_{sdCOLD})}{k_1} = 58°C$$

Similarly for output diode we have

$$T_{JDIODE} = T_{amb} + \frac{(V_{fHOT} - V_{fCOLD})}{k_2} = 89°C$$

The results are showing sufficient thermal margin for all components. At the maximum ambient temperature of 55°C the output diode junction temperature will be 113°C which is OK, but we can consider changeover to FR-4 substrate with 70µm copper and bigger heatsink surface.

The picture of converter prototype is given in Fig.8.

V. CONCLUSION

In this paper the design and analysis of 10W forward converter are presented.

The prototype was built and tested. The results verified that the full load efficiency is about 83%.

Further improvements are possible thorough Active Clamp Reset with controller change and Synchronous Rectifier in the secondary. The efficiency will go over 90%.

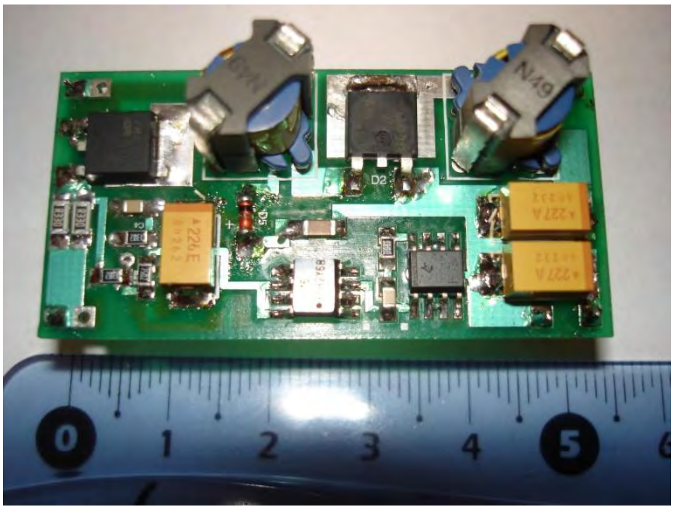

Fig.8. Converter prototype

ACKNOWLEDGEMENT

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