Design and Realization of a Low Noise Medical AC/DC Converter

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Abstract – **In this paper the design of a low EMI universal input mains power supply is presented. The prototype has been built and experimental results are presented to support the theoretical analysis and to demonstrate the converter performance. The single switch flyback topology is used because of its simplicity and small number of components.**

Keywords – **CCM Flyback, EMI, Leakage current, PWM.**

I. Introduction

Power supplies designed for industrial applications are not suitable for use in medical equipment such as X-ray, CT scanners, MRI and patient monitors. Medical equipment operates with low level signals and it is more sensitive to electromagnetic interference (EMI). The Patients exposure to the smallest leakage currents may pose a threat to their life. The maximum permissible leakage current for medical equipment is no more than few hundred μA worldwide. That requirement is difficult to achieve while keeping electromagnetic interference low. Switching power supplies generate EMI and require filters to limit electrical noise. Capacitors in these filters produce leakage currents. The more effective filter produces higher leakage currents. A better approach is to minimize the amount of interference at the origin.

II. EMI reduction

The power switches in switching power supplies are typically field effect transistors (FETs) and they are forced to switch as quickly as possible. Abrupt voltage and current transitions needed for high efficiency are the main causes of the noise. Because of that, input and output voltages contain low frequency ripple from 100 kHz to few MHz and high frequency content (switching spikes) with harmonics approaching 100MHz. Lowering the frequency and increasing the transition times can dramatically reduce ripple and spike amplitude.

PWM controller LT1738 from Linear Technology is a fixed frequency, single output current mode switching regulator optimized for single switch topologies such as boost and flyback, with unique circuitry to control the voltage and current slew rates of the external N-channel MOSFET.

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As seen on Fig.1 capacitor C_V provides the voltage slew rate feedback, while the current slew rate occurs by means of the sense resistor R_{SEN}. Because of the voltage slew control, MOSFET ringing is reduced and clamping circuits or snubbers in the most cases are not required. The slew rates are simply adjustable through changing the values of two resistors. The trade-off between noise and converter efficiency must be made, but fortunately the loss of efficiency is less than 10% in most cases.

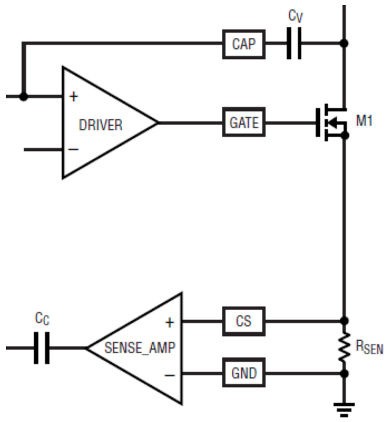

Fig.1. Slew control

DC/DC controller has all protection features including gate drive lockout for low V_{IN}, soft-start, output current limit, short circuit current limit, gate drive overvoltage clamp and input undervoltage lockout.

III. Design and analysis

The task is to design a 40W CCM flyback converter using current mode controller with careful choice of operating parameters and components. Achieving the lowest possible noise is the primary objective. The footprint size must be around 120x80mm.

First we will choose the switching frequency to be around 100 kHz, which is a compromise between the efficiency and size of the magnetics. Knowing that, a good choice of core for the transformer is PQ26/25, N95 material from TDK. Reinforced insulation is a must, but the effectiveness of which must be verified by dielectric strength testing. This means subjecting the insulation to a higher voltage than that at which it operates.

Single-section EMI filters with one stage of common mode and differential mode attenuation take the least space and have the lowest cost but require careful attention to the details. Y capacitors are planned but will not be populated.

Design specifications are given in Table I.

TABLE I
DESIGN SPECIFICATIONS

		Min	Typ	Max	
Input voltage	V_{IN}	100	220	264	V_{AC}
Output voltage 1	V_{O1}		+12		V
Output power	P		40		W
Full load efficiency	η		75		%
Switching frequency	f_{SW}		100		kHz

We will now calculate the basic parameters for the transformer, using the following equations:

$$N = \frac{N_P}{N_S} = \frac{V_{DCMIN}}{V_O + V_D} \frac{D_{MAX}}{1 - D_{MAX}} \quad (1)$$

$$I_P = \frac{I_O}{N} \frac{1}{1 - D_{MAX}} + \frac{\Delta I_P}{2} \quad (2)$$

$$L_P = V_{DCMIN} \frac{D_{MAX} T}{\Delta I_P} \quad (3)$$

$$N_P = \frac{L_P I_P}{B_{MAX} A_E} \quad (4)$$

$$I_{PRMS} = \sqrt{D_{MAX} \left(I_P^2 - \Delta I_P I_P + \frac{\Delta I_P^2}{3} \right)} \quad (5)$$

$$g = \frac{\mu_0 N_P^2 A_E}{L_P} \quad (6)$$

The results are given in Table II.

TABLE II
BASIC PARAMETERS

		Max	Typ	Min	
Duty cycle	D	0.49	0.24	0.21	
Number of prim. turns	N_P		29		
Number of sec. turns	N_S		4		
Primary peak current	I_{PPEAK}	1.28	0.98	0.96	A
Primary RMS current	I_{PRMS}	0.63	0.29	0.26	A
Secondary peak current	I_{SPEAK}	6.53	4.38	4.21	A
Secondary RMS current	I_{SRMS}	4.66	3.82	3.74	A

Now it is time to wind the transformer. We will use a bundle of 7 twisted wires - 0.2 mm enamelled copper wire for the primary and a triple insulated Litz wire with 0.28 mm wires for the secondary, in order to minimize copper losses taking into account the skin effect and to fulfil demands for reinforced insulation.

Knowing specific core losses we can now calculate the loss in magnetic component (Table III). Total transformer power loss at $100V_{AC}$ input voltage is 1.5W. This results in approximately 43°C rise above ambient temperature. Satisfied with the results, we will keep the chosen core geometry.

TABLE III
TRANSFORMER LOSSES

		Max	Typ	Min	
Core effect. volume	V_E		6.53		cm^3
Specific core losses	P_V		0.14		W/cm^3
Core loss	P_{CORE}		130		mW
Primary resistance	R_{PRI}		137		mΩ
Primary loss	P_{PRI}	55	11	9	mW
Secondary resistance	R_{SEC}		61		mΩ
Secondary loss	P_{SEC}	1.32	0.89	0.85	W

Power switch losses can be expressed by the equation

$$P_{FET} = P_{COND} + P_{ON-OFF} + P_{QOSS} \quad (7)$$

where

P_{COND} is the conduction loss given by

$$P_{COND} = I_{RMS}^2 R_{DS} \quad (8)$$

P_{ON-OFF} is the turn-on-off switching loss given by

$$P_{ON-OFF} = \frac{V_{DS} I_P (t_{ON} + t_{OFF}) f_{SW}}{2} \quad (9)$$

and

P_{QOSS} is the capacitance charge loss given by

$$P_{QOSS} = \frac{C_{OSS} V_{DS}^2 f_{SW}}{2} \quad (10)$$

As a result of the slew rate control we can expect for t_{ON} and t_{OFF} to be around 200ns each, so the MOSFET's dissipation would be excessive. Using Eq. (7) to (10) we have calculated its dissipation given in Table IV.

TABLE IV
PRIMARY FET DISSIPATION

IRFBC40		Max	Typ	Min	
ON resistance	R_{DS}		1.2		Ω
Output capacitance	C_{OSS}		48		pF
ON time	t_{ON}		200		ns
OFF time	t_{OFF}		200		ns
Conduction loss	P_{COND}	0.71	0.15	0.12	W
Switching loss	P_{ON-OFF}	5.12	7.25	8.45	W
Capacitance charge loss	P_{QOSS}	0.09	0.33	0.47	W
Total loss	P_{TOT}	5.92	7.73	9.04	W

IV. Realization

AC/DC converter was built on two layer FR-4 substrate with 35µm copper with a footprint of 120x80mm. The transformer is wounded on through hole coil former according to calculations. Output voltage is further filtered out by the added LC filter. All electrolytic capacitors are low ESR aluminum electrolytic capacitors.

Furthermore we have measured full load efficiency at various input voltages. For practical reasons we have used input voltages from 120 to 360V_{DC}. This measure gives a slightly better result than the actual value. The results are given in Table V. The efficiency is between 70 and 77% at full load.

TABLE V
EFFICIENCY

		Min	Typ	Max	
Input voltage	V_{IN}	120	300	360	V_{DC}
Input current	I_{IN}	0. 431	0.183	0.159	A
Input power	P_{IN}	51.70	55.00	57.10	W
Efficiency	η	77.37	72.72	70.05	%

Using variable isolation mains transformer and resistive load we have recorded the waveforms at the point of interest.

The drain waveforms of the primary power switch at full load and input voltages of 100 and 200V_{AC} are given in Figs. 2 and 3. As seen on the waveforms the converter is working in CCM mode. The wideband harmonic activity is entirely absent, without ringing and fast rise and fall times in the drain waveform of the power switch.

Characteristic gate voltage waveform can be seen in Fig. 4. The edges of the square wave drain waveform are slewed to trapezoidal shape (Fig. 5 and 6). As we can see the transition times are more than 200ns (in "normal" converters usually 50 to 100ns) and the net result is low harmonic content but the price is paid through efficiency reduction.

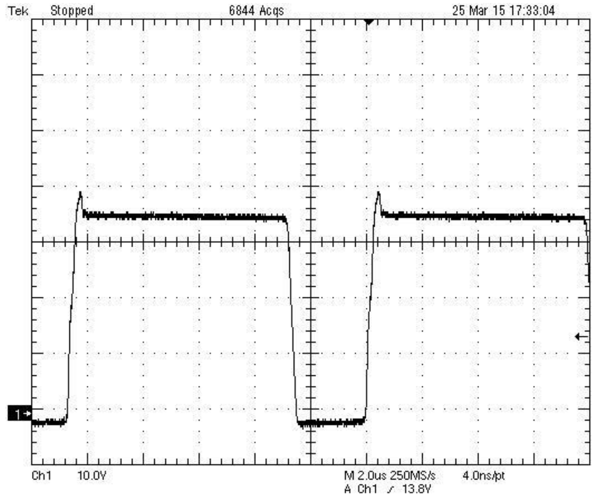

Fig.3. Drain voltage waveform at 200V_{AC}

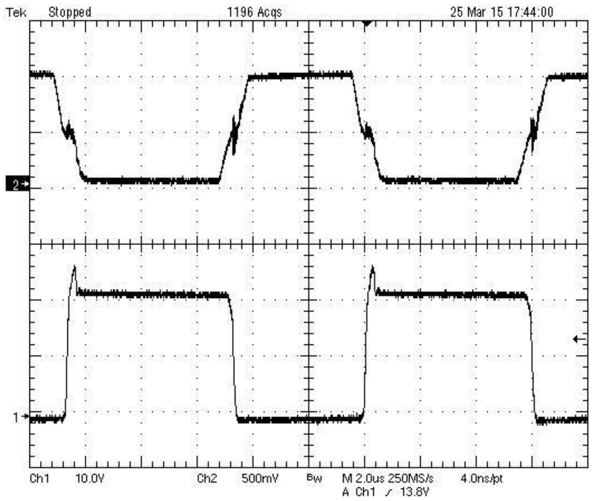

Fig.4. Drain and gate voltage waveform at 100V_{AC}

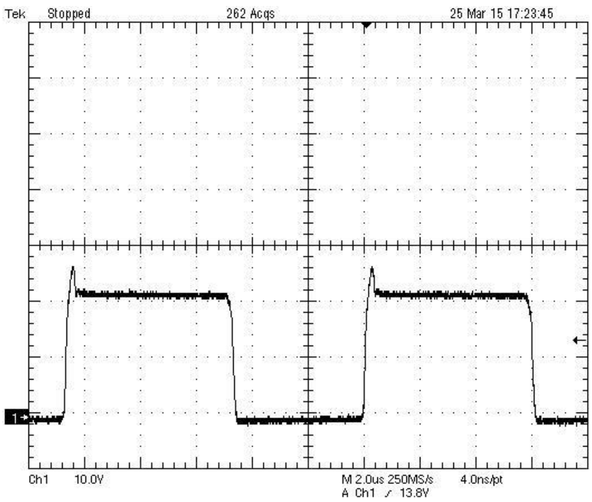

Fig.2. Drain voltage waveform at 100V_{AC}

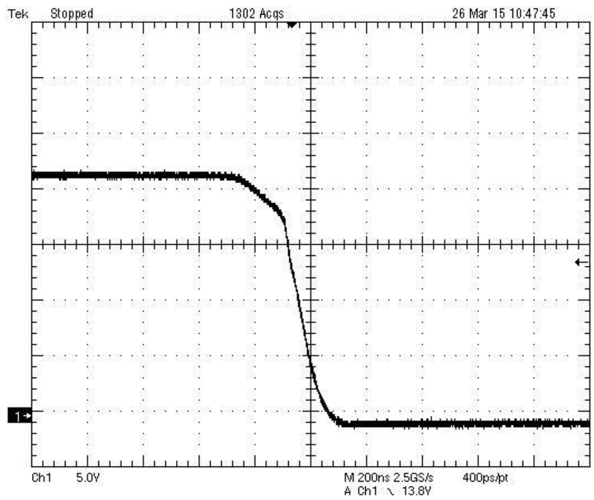

Fig.5. Drain voltage ON slew rate

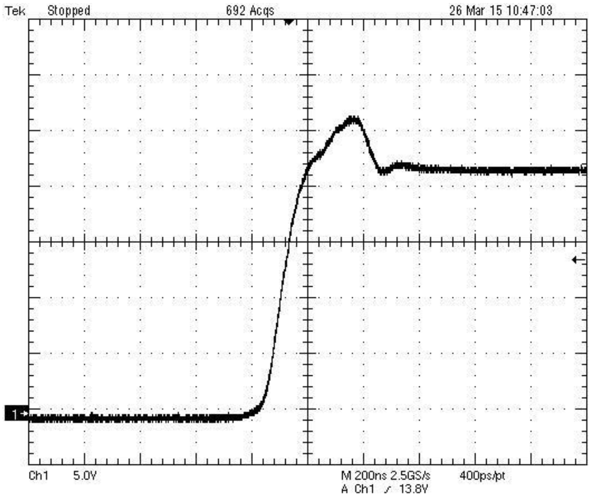

Fig.6. Drain voltage OFF slew rate

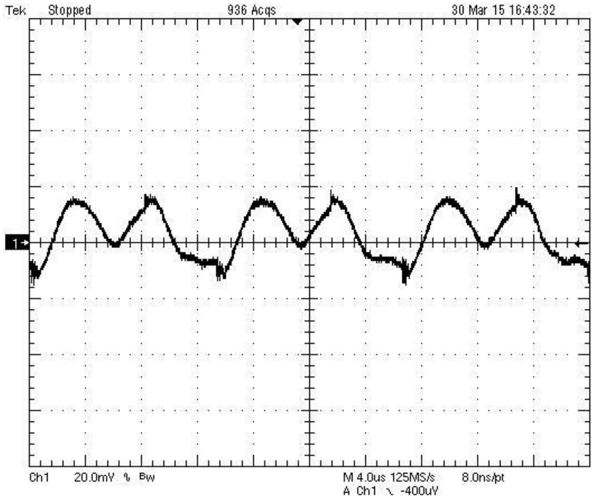

Fig.7. Input voltage ripple at full load

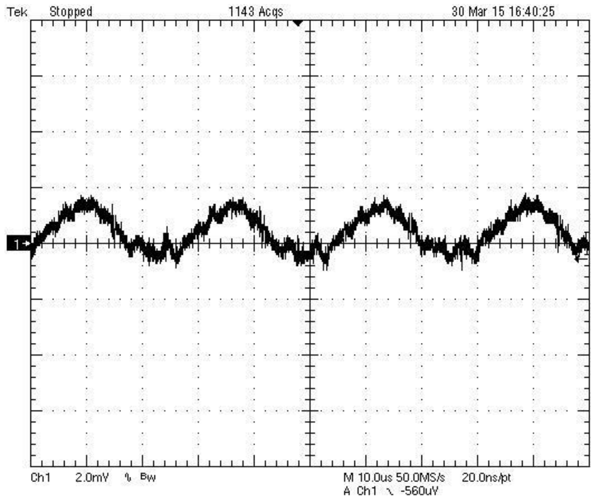

Fig.8. Output voltage ripple at full load

The input voltage ripple is around 30mV$_{pp}$ (Fig.7) and contains only fundamental frequency without ugly spikes (measured with DC input voltage – Line Impedance Stabilization Network was not available). After the output LC filter the residual noise is 2mV$_{pp}$ at full load and bandwidth 150 MHz (Fig.8) without high frequency components.

The picture of converter prototype is given in Fig.9.

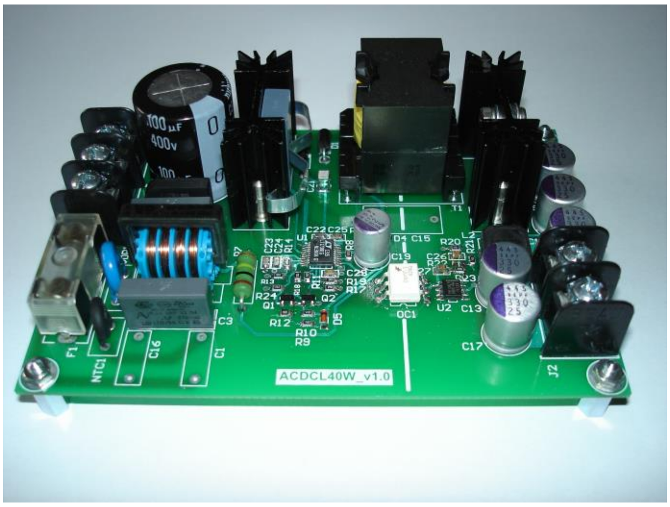

Fig.9. Converter prototype

V. Conclusion

In this paper the design and analysis of 40W CCM flyback converter are presented. The prototype was built and tested. The amount of electromagnetic interference is reduced and only a small EMI filter is needed to meet the EMC requirements. With only a small amount of filtering, without Y capacitors, leakage currents are kept low, satisfying the safety requirements. The results verified that the full load efficiency is over 70%. The converter is cheap and easy to manufacture. With minor changes we can make different versions of this power supply.

Acknowledgement

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References

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