EECS166A - Lab 3 Report
Boost Converter Design Project

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Title	Lab 3
Day of Session	9:00AM
Group Number	7
Group Members	Andrey Miroshnikov
Date of Submission	03/16/2018

1 Introduction

The goal of this lab was to design, assemble and test a boost converter with a given specification. The result was a converter with an efficiency of over 90% (in closed-loop configuration).

2 Boost Converter Specification

Table 1: Boost Converter Spec

Parameters	Values
Input Voltage	20-40V
Output Voltage	70V
Output Power	20W
Output Voltage Ripple	0.2% of rated output voltage
Switching Frequency	200kHz
Conduction Mode	CCM at 20W.
	Can be DCM at lower power.

3 Boost Converter Overview

3.1 Block Diagram

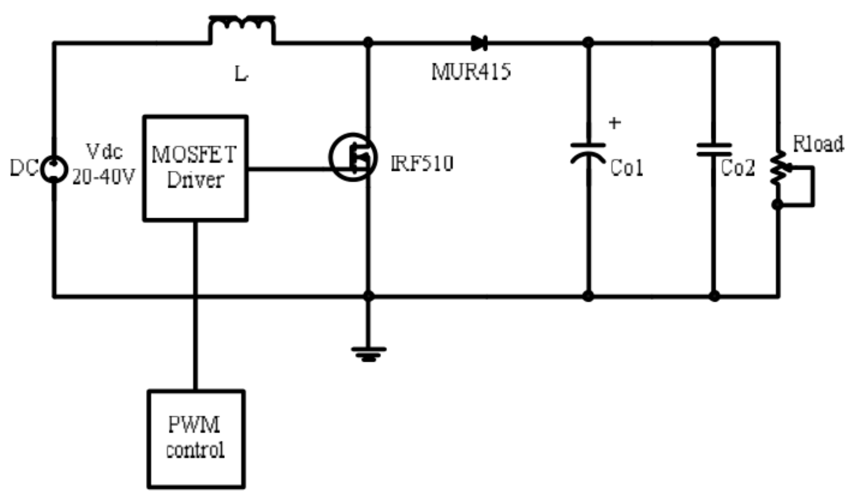

Figure 1: Boost converter block diagram.

The boost converter consists of several blocks: the basic boost converter itself (part of the power stage), the MOSFET driver and PWM control (both part of control stage). The boost converter had high voltage signal on it where the input was between 30V and 40V DC and the output was

70V DC with small amount of ripple. The inductor had large current spikes however. The MOSFET driver and PWM controller were powered by a low voltage, 12V DC power rail. The ICs used for the driver and PWM controller were IR4427 and SG3524 respectively.

4 Calculations

The inductor was designed to be $171uH$ by using Ap product inductor design. The switching frequency was set to $200kHz$ by using the external resistor and capacitor R_t and C_t. The capacitor was set to $1nF$ and the resistor was calculated using $f = \frac{1.3}{R_t C_t}$, giving a resistance of $6.5k\Omega$.

5 Input = 30V, Pout = 20W Simulation

The boost converter was simulated in closed-loop configuration. Tab. 2 shows the inductor current and capacitor voltage. Due to feedback, the voltage ripple was approximately $\frac{0.21}{70} * 100 = 0.3\%$, thus exceeding the specification.

Table 2: Simulation Results

Parameters	Peak Max	Peak Min	Trough Max	Trough Min	Difference
Inductor Current	$1.4791A$	$1.0213A$	$418.665mA$	$27.213\mu A$	1.479A
Capacitor Voltage	$70.121V$	$70.108V$	$69.929V$	$69.911V$	0.21V

5.1 Output Voltage

The output voltage had a fairly long transient time of about 6.5ms. The ripple however, was very small.

Figure 2: Output capacitor voltage.

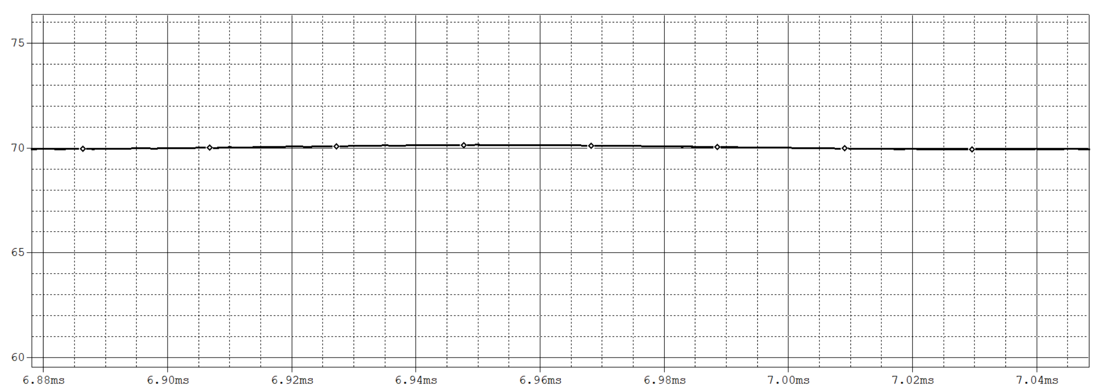

Figure 3: Output capacitor voltage zoomed in.

5.2 Inductor Current

The inductor current also had a transient time of about 6.5ms. The current also had an envelope frequency of about 7kHz.

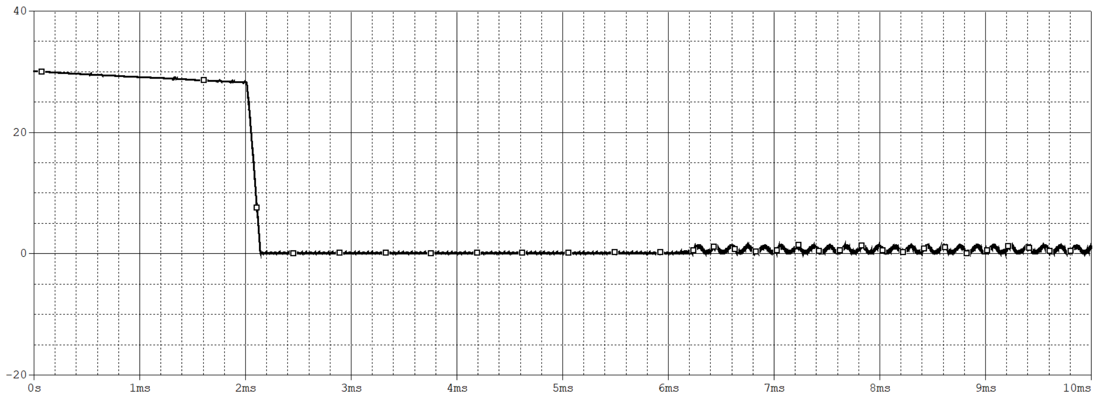

Figure 4: Inductor current.

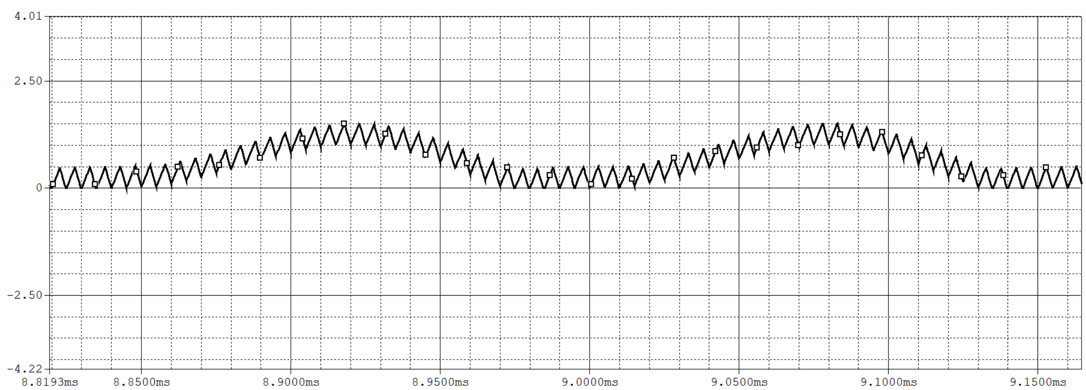

Figure 5: Inductor current zoomed in.

5.3 MOSFET Driver Signal

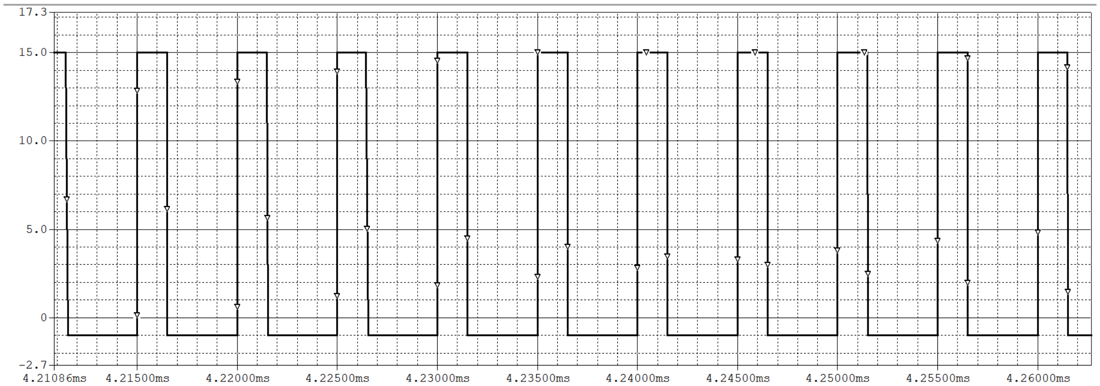

Figure 6: Driver signal voltage.

6 Boost Converter Open-Loop Schematic

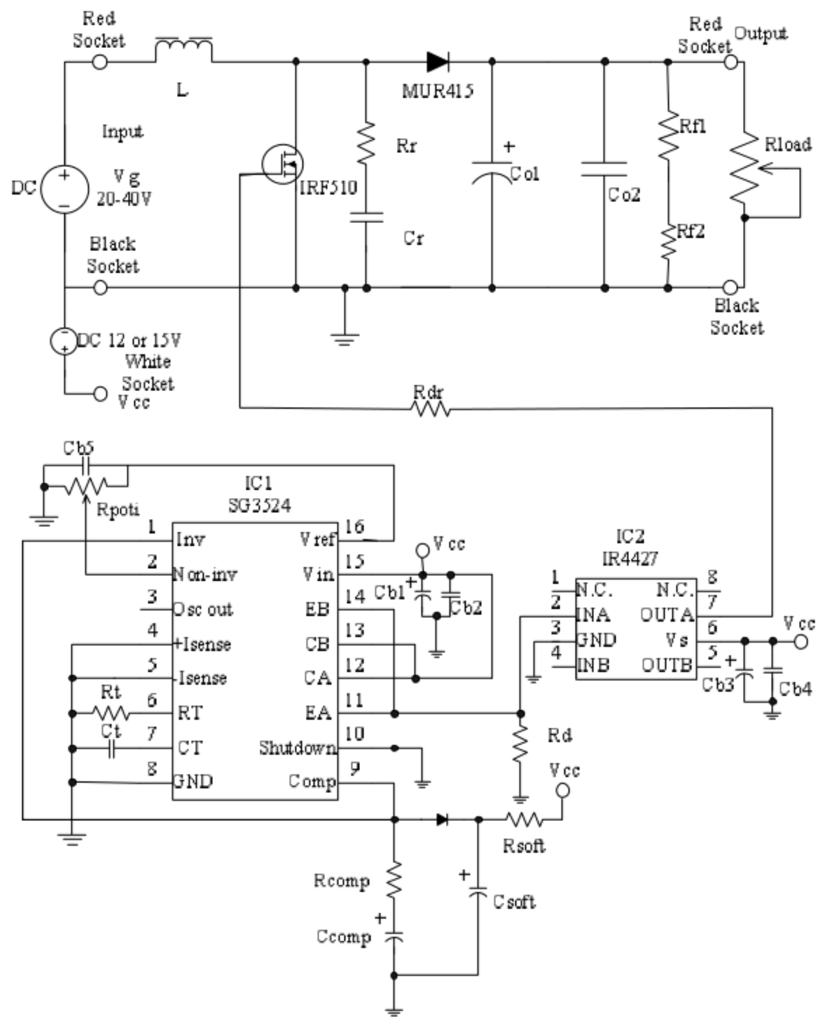

Figure 7: Boost converter open-loop schematic.

The duty cycle of the converter was controlled manually by using the R_{poti} potentiometer.

7 Boost Converter Closed-Loop Schematic

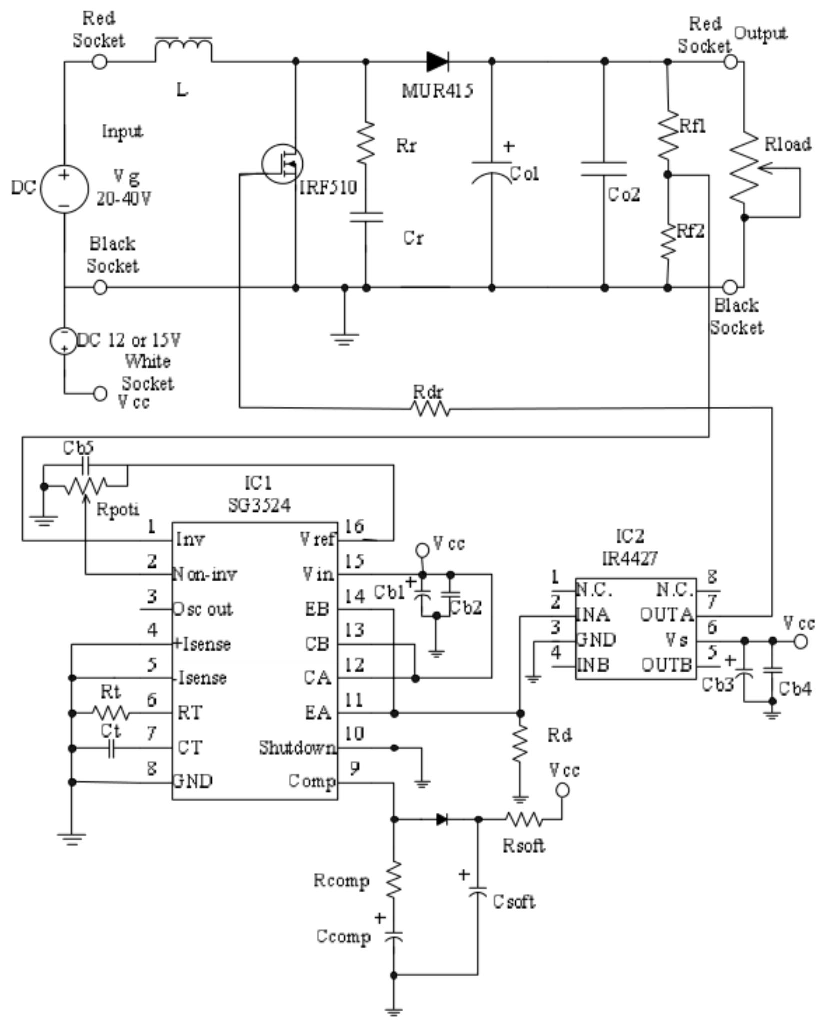

Figure 8: Boost converter closed-loop schematic.

The duty cycle was controlled by comparing the voltage divider output of resistors R_{f1} and R_{f2} with the reference voltage from R_{poti}.

8 Bill of Materials

	Label	Value/Character	Quantity
Capacitors			
timing cap	Ct	1nF ceramic	1
bypass cap	Cb2, Cb4, Cb5	0.47µ F ceramic 50V	3
bypass cap	Cb1, Cb3	4.7µ F electrolyti 50V	2
output cap	Co1	100µ F electrolytic 100V	1
output cap	Co2	0.68µ F polyester 100V	1
snubber cap	Cr	330pF ceramic	1
compensation cap	Ccomp	4.7µ F electrolyti 50V	1
soft start cap	Csoft	4.7µ F electrolyti 50V	1
Resistors			
measruement R (between the input voltage and inductor) 1ohm 1W			1
timing R	Rt	5.6k 1/4 W	1
driver R	Rd	4.7k 1/4 W	1
driver R	Rdr	10 1/4 W	1
feedback R	Rf1	27k 1/4 W	1
feedback R	Rf2	1k 1/4 W	1
snubber R	Rr	50 3 W	1
duty ratio adjust	Rpoti	10k	1
compensation	Rcomp	10k	1
soft start R	Rsoft	200k	1
IC's and Semiconductors			
PWM controller	UC3524	PWM controller	1
driver	IR4427	MOSFET driver	1
MOSFET	IRF510	5A 100V	1
diode	MUR415	4A 150V	1
diode	1N4148	fast signal diode	1
Magnetic parts			
core	0P42213-UG	magnetic core	1
bobbin	B-2213	bobbin	1
clamp	PC-2213	clamp	1
winding wire	22 AWG	AWG 22 magnetic wire	enough
Accessories			
socket	16Dip	16pin dip	1
socket	8Dip	8pin dip	1
breadboard			1
banana plug		black	1
banana plug		red	2
banana plug		white	1
breadboard stands		bolts	4
		nuts	4
heat sink		heat sink	1
		bolt	1
		nut	1

Figure 9: Boost converter bill of materials.

9 PWM Circuit Test

9.1 IC1 and IC2 V_{dd} Rail

Mean voltage on the V_{dd} rail was $12.188V$.

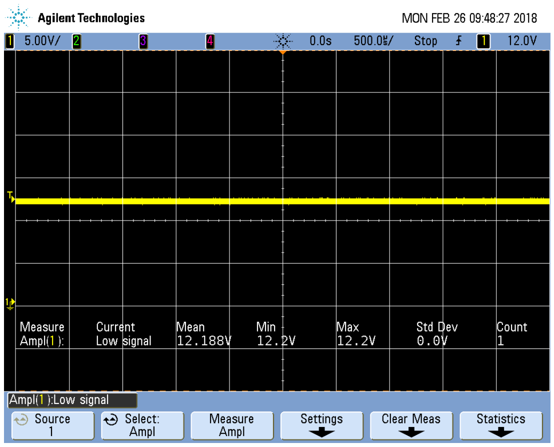

Figure 10: IC1 V_{dd}.

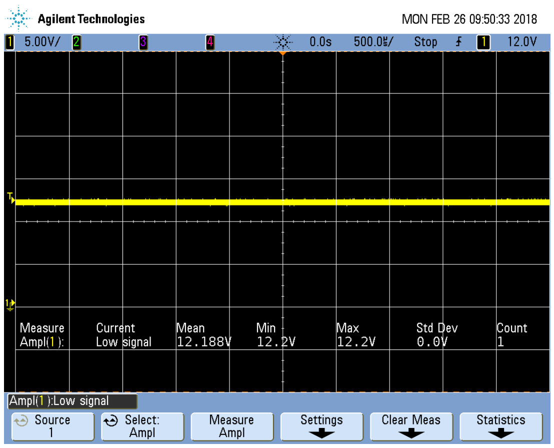

Figure 11: IC2 V_{dd}.

9.2 IC1 Pin 16 V_{ref}

Mean reference voltage was $5.0000V$.

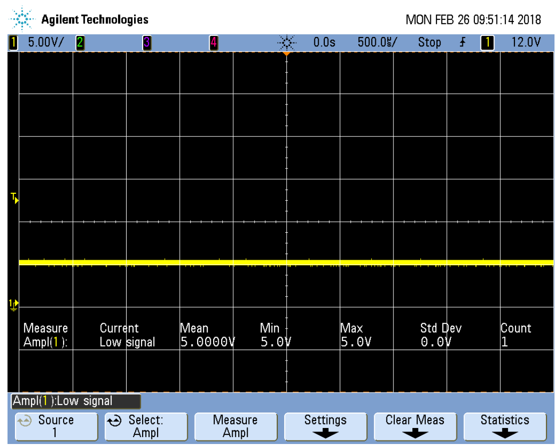

Figure 12: IC1 V_{ref}.

9.3 Sawtooth Waveform

Sawtooth waveform had the frequency of $187kHz$, duty cycle of 49.5% and amplitude of $3.13V$.

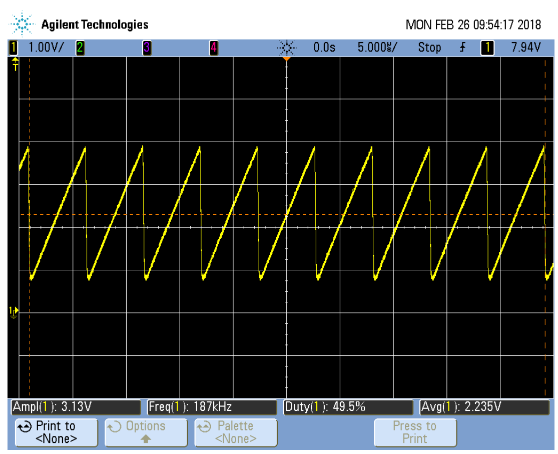

Figure 13: IC1 sawtooth waveform.

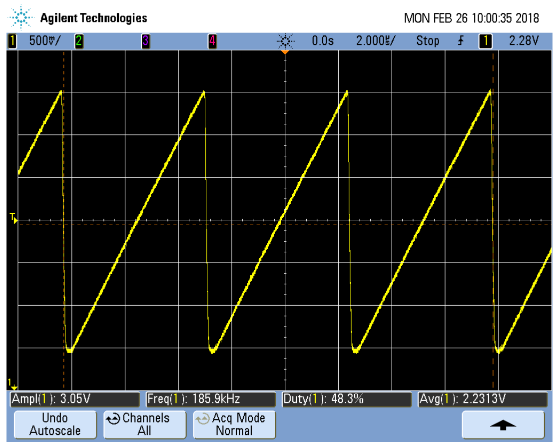

Figure 14: Zoomed in view of sawtooth waveform.

9.4 PWM Signal

PWM waveform had the frequency of $184.5kHz$, duty cycle of 60.1% and amplitude of $10.06V$.

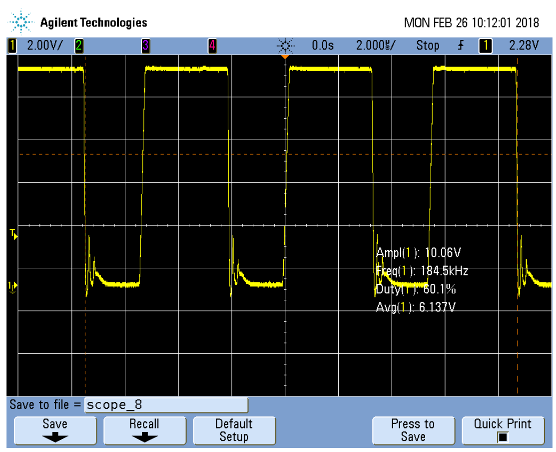

Figure 15: PWM signal.

10 Open-Loop Test

10.1 Input = 30V

10.1.1 MOSFET Voltage V_{ds}

MOSFET V_{ds} had the frequency of $184.3kHz$, duty cycle of 55.5% and amplitude of $70.625V$.

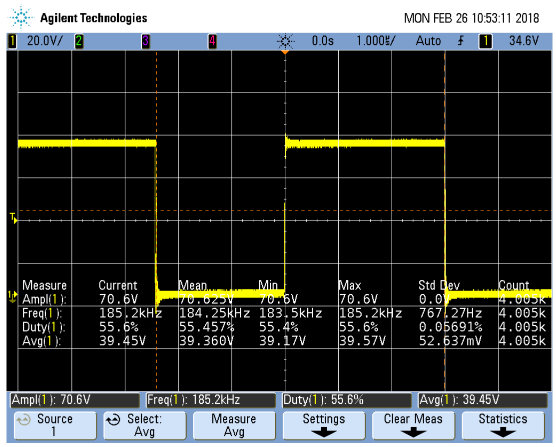

Figure 16: MOSFET V_{ds}.

10.1.2 Inductor Current

The inductor ripple was $625mA$ as the screenshot shows, switching spikes were present.

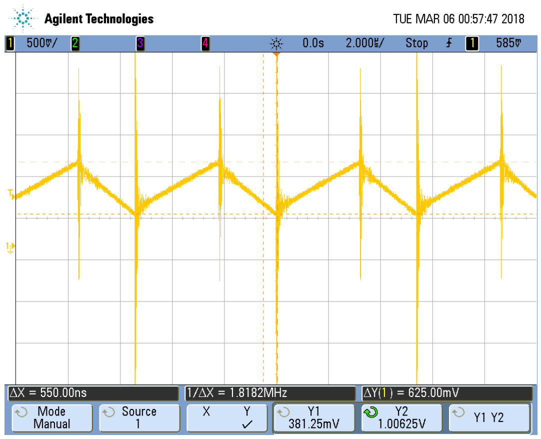

Figure 17: Inductor current.

10.1.3 Output Voltage

The output voltage ripple was $1.9V$ or 2.7% of rated output voltage. The specification was not met in the open-loop configuration because the larger $100\mu F$ output capacitor was not soldered until the closed-loop configuration was tested.

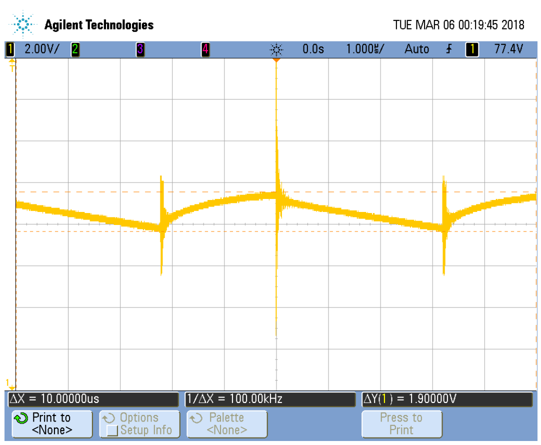

Figure 18: Capacitor voltage.

10.2 Input = 40V

10.2.1 MOSFET Voltage V_{ds}

MOSFET V_{ds} had a duty cycle of 40.8% and amplitude of $70.6V$.

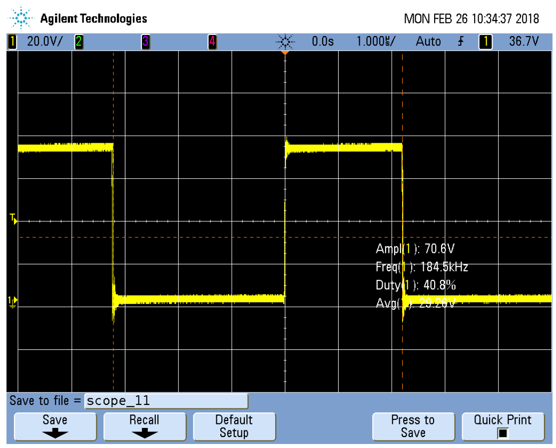

Figure 19: MOSFET V_{ds}.

10.2.2 Inductor Current

The inductor ripple was $662.5mA$.

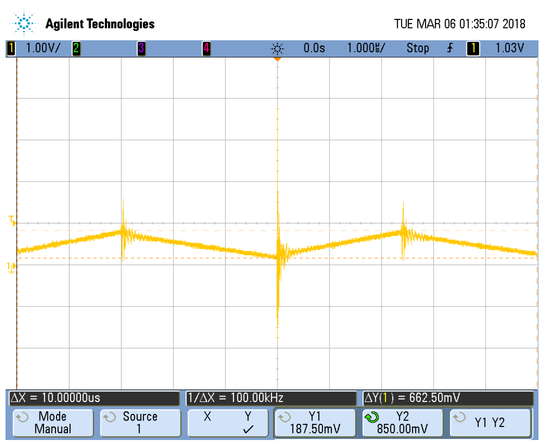

Figure 20: Inductor current.

The switching spikes were smaller because the input voltage was closer to the output voltage.

10.2.3 Output Voltage

The output voltage ripple was $1.375V$ or 1.96% of rated output voltage.

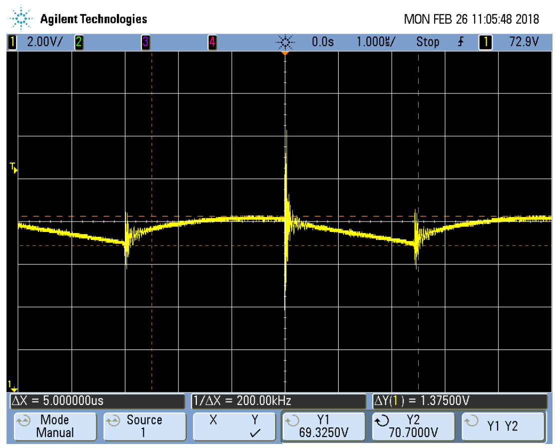

Figure 21: Capacitor voltage.

10.3 Efficiency Calculation

The efficiency was calculated using the following equation:

$$\eta = \frac{V_O I_O}{V_g I_g - I_g^2} \tag{1}$$

The I_g^2 term accounted for the power dissipated by the 1Ω resistor.

Table 3: Open-Loop efficiency results.

P_O/W	R_O/Ω	V_g/V	I_g/A	V_O/V	I_O/A	η
20	245	29.925	0.725	70.087	0.282	0.934
15	327	29.944	0.550	70.044	0.213	0.923
10	490	29.831	0.367	70.209	0.142	0.922
5	980	29.848	0.186	69.978	0.072	0.907
20	245	39.803	0.523	69.737	0.279	0.947
15	327	39.416	0.403	70.090	0.213	0.950
10	490	39.420	0.275	71.052	0.143	0.944
5	980	40.180	0.144	70.980	0.072	0.891

Results showed that the open-loop boost converter had a higher efficiency at higher loads as well as at a higher voltage. Both of those observations made sense since the converter operated in CCM at $20W$ output power as well the boost converter in general having a higher efficiency at lower duty cycles (due to higher input voltage).

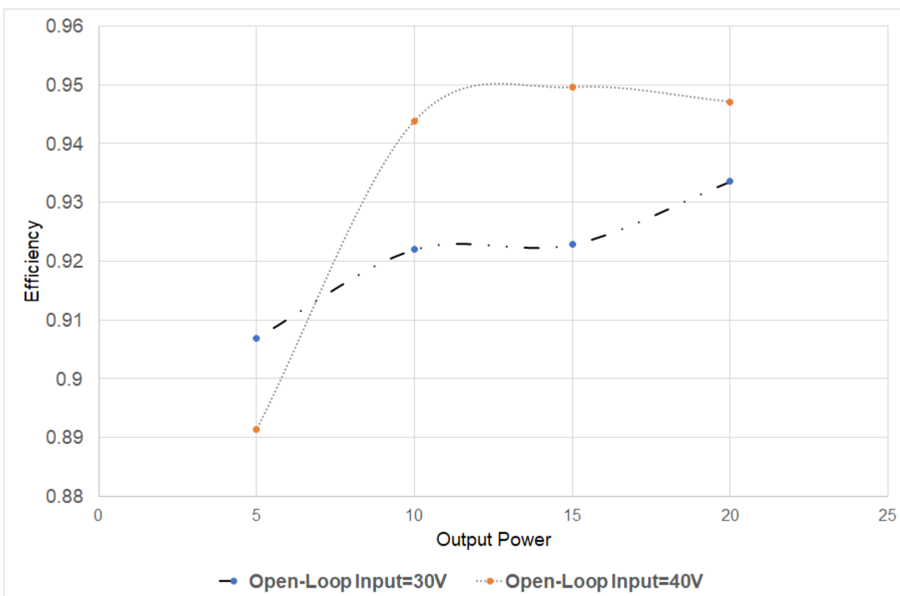

Figure 22: Open-Loop efficiency plot.

10.4 DCM Inductor Current Waveform

Increasing load resistance to about $1500k\Omega$ or about $3.3W$ had put the boost converter into DCM. During the second half of switching cycle, the inductor current dropped below zero before rising back to zero. The negative current value is likely due to the output capacitance.

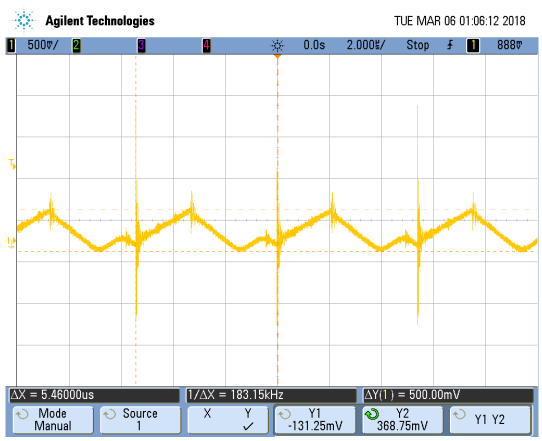

Figure 23: Inductor current in DCM.

11 Closed-Loop Test

11.1 Input = 30V

11.1.1 SG3524's Inverting and Non-Inverting Inputs

The input waveforms have a lot of noise on top of them, as well as switching spikes.

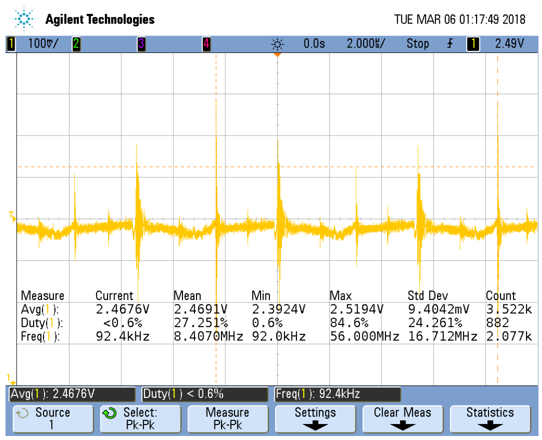

Figure 24: Inverting input of SG3524.

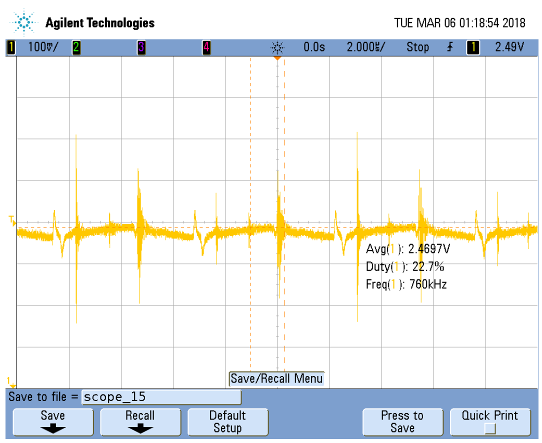

Figure 25: Non-inverting input of SG3524.

11.1.2 MOSFET Voltage V_{ds}

MOSFET V_{ds} had a duty cycle of 42.2% and average voltage of $29.139V$. Due to the feedback loop, the duty cycle was significantly lower.

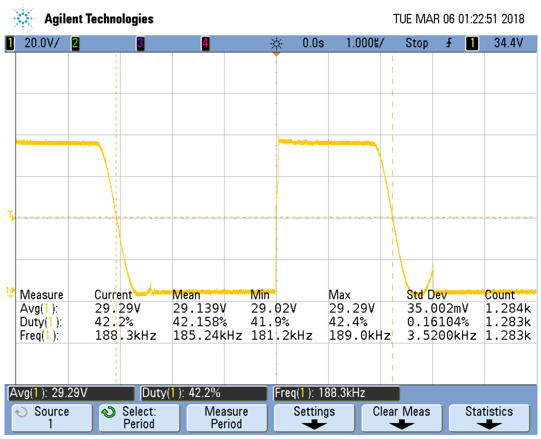

Figure 26: MOSFET V_{ds}.

11.1.3 Inductor Current

The inductor ripple was $625mA$. As with the open-loop case, switching spikes were present.

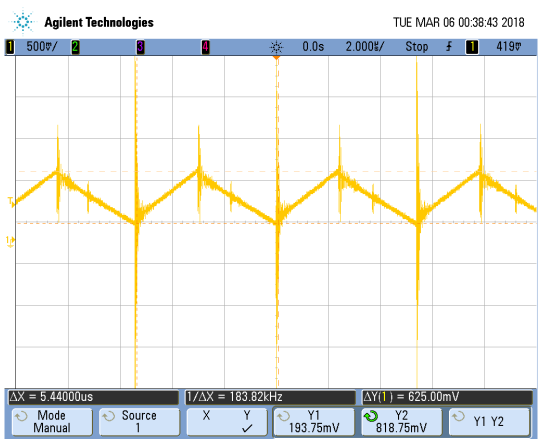

Figure 27: Inductor current.

11.1.4 Output Voltage

Output voltage was $70.112V$ and the ripple was $47.50mV$ or 0.07% of the rated output voltage. After soldering the bigger $100\mu F$ capacitor and implementing the feedback loop, the ripple had reduced to below specified level of 0.2%.

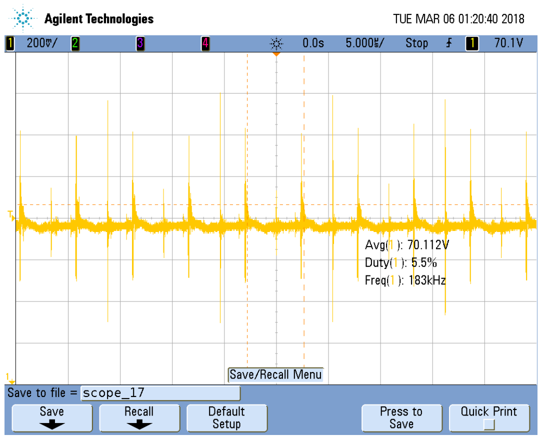

Figure 28: Capacitor voltage.

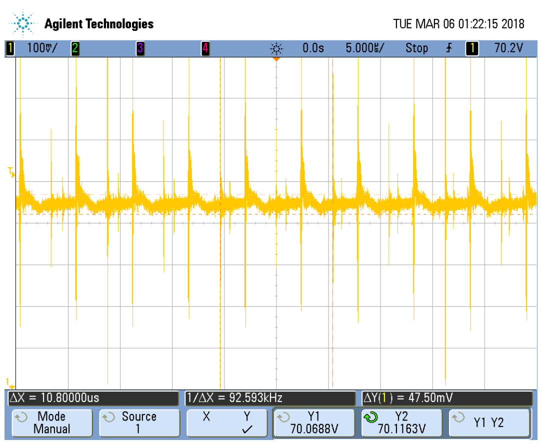

Figure 29: Showing output ripple measurement.

11.2 Input = 40V

11.2.1 MOSFET Voltage V_{ds}

MOSFET V_{ds} had the frequency of $184.71kHz$, duty cycle of 45.3% and average voltage of $39.020V$.

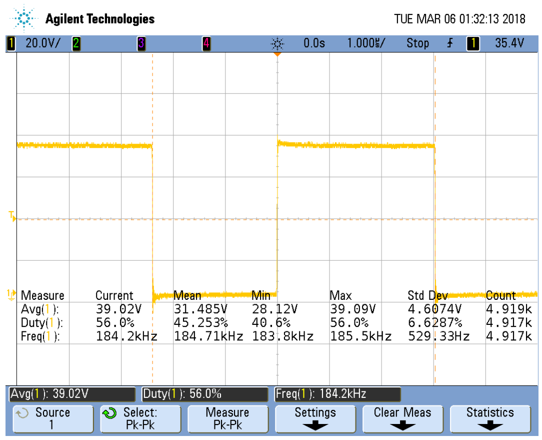

Figure 30: MOSFET V_{ds}.

11.2.2 Inductor Current

The inductor ripple was $620mA$. As with the open-loop case, switching spikes were present. More high frequency ripple also seems to be present during the transition from on-time to off-time of the MOSFET.

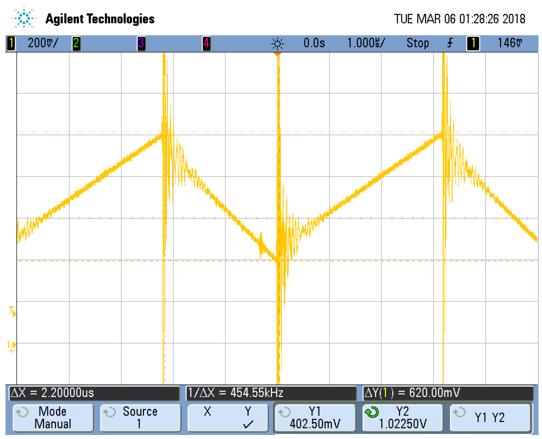

Figure 31: Inductor current.

11.2.3 Output Voltage

Output voltage was $70.064V$ and the ripple was $106.25mV$ or 0.15% of the rated output voltage. This ripple was double of the $V_g = 30V$ case, however the ripple was still within spec. The output also had voltage spikes about $12V$ in amplitude.

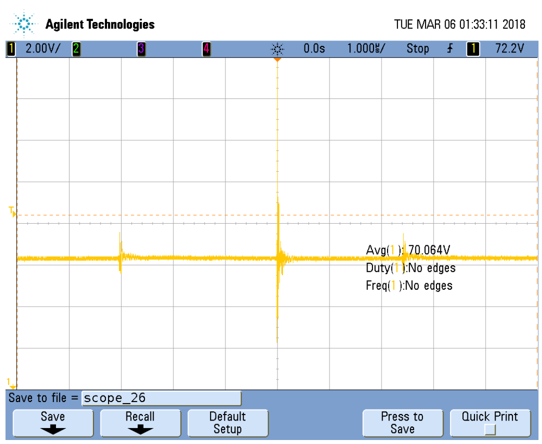

Figure 32: Capacitor voltage.

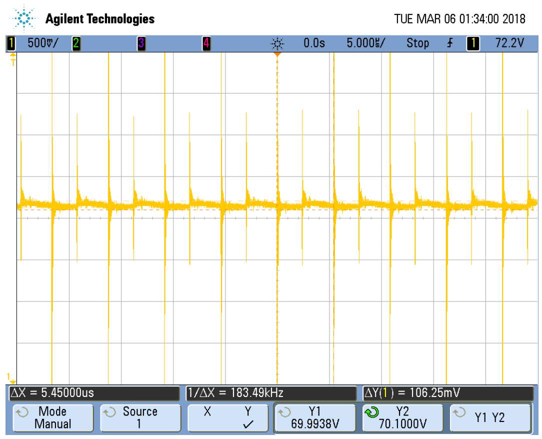

Figure 33: Showing output ripple measurement.

11.3 Efficiency Calculation

The same equation was used to compute the efficiency as the open-loop case.

Table 4: Open-Loop efficiency results.

P_O/W	R_O/Ω	V_g/V	I_g/A	V_O/V	I_O/A	η
20	245	29.755	0.715	69.765	0.280	0.941
15	327	29.960	0.543	70.052	0.212	0.930
10	490	29.855	0.366	70.061	0.142	0.922
5	980	29.793	0.186	70.073	0.072	0.910
20	245	39.203	0.524	70.560	0.280	0.968
15	327	39.441	0.399	70.046	0.212	0.953
10	490	39.470	0.269	70.042	0.142	0.943
5	980	39.401	0.140	70.048	0.072	0.911

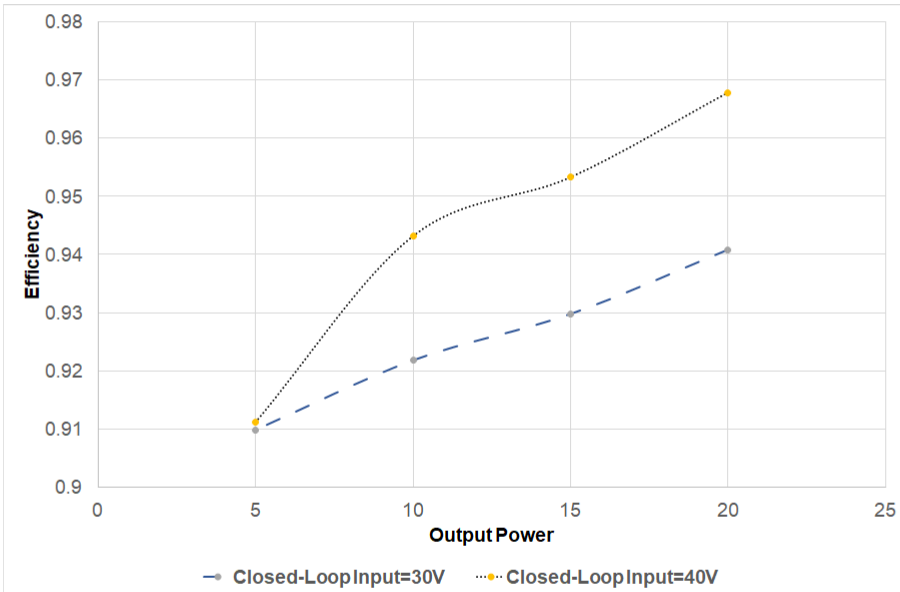

Figure 34: Closed-Loop efficiency plot.

The closed-loop converter has shown a similar trend in terms of output power and input voltage. The overall efficiency of the converter has increased for all test cases however. The feedback allows the converter to operate at optimal duty cycle regardless of input voltage or load.

11.4 DCM Inductor Current Waveform

Increasing load resistance to about $1500k\Omega$ or about $3.3W$ had put the boost converter into DCM. During the second half of switching cycle, the inductor current dropped below zero before rising back to zero.

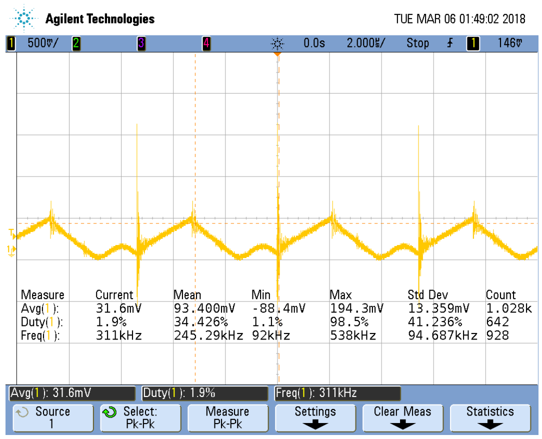

Figure 35: Inductor current in DCM.

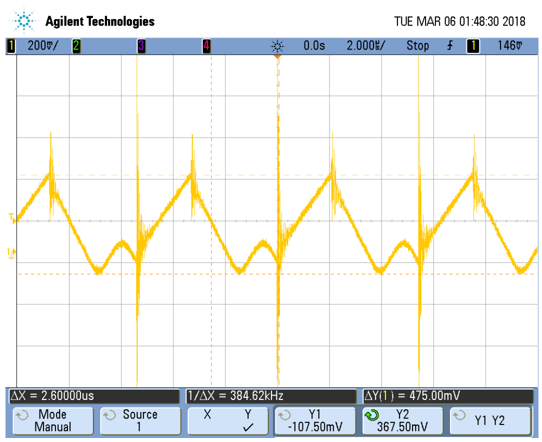

Figure 36: Inductor current zoomed in.

12 Assembly and Debugging

The inductor was wound round a plastic bobbin which was then placed inside a magnetic ferrite core (shown in upper left Fig. 37). The components were soldered to pre-made PCB with plenty of clearance for each component. The MOSFET heatsink was isolated using a special type of thermal tape. This was necessary because the TO-220's heatsink tab is connected to the drain terminal and hence is dangerous when the boost converter was in operation. A simple jumper selector allowed to switch from open-loop to closed-loop operation.

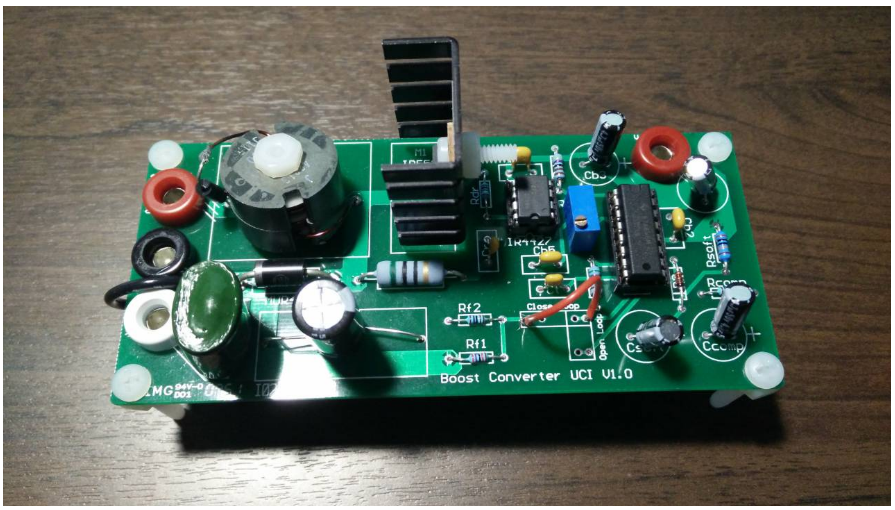

Figure 37: Boost converter circuit.

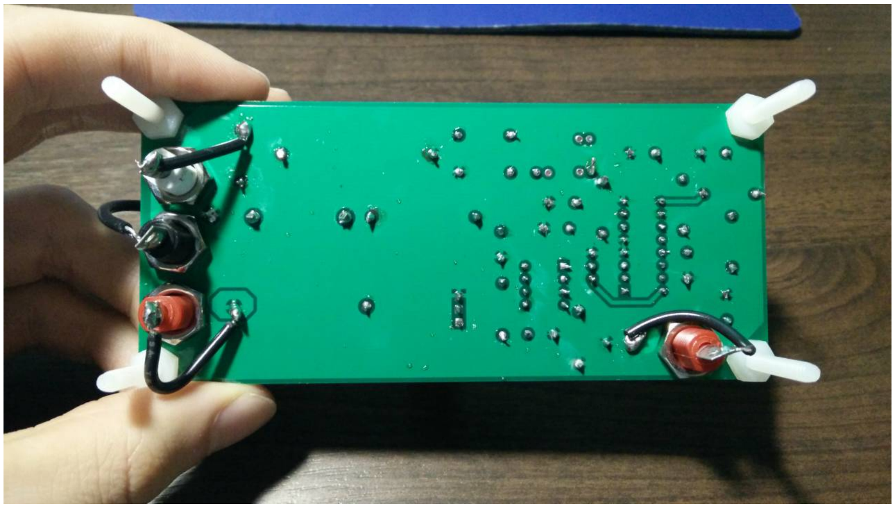

Figure 38: Bottom side of PCB.

The circuit operated correctly first time because all of the connections and solder joints were check before starting any tests.

13 Improving The Project

The converter would operate better if it adhered to strict EMI standards. If the lab also covered how to design filters for the switching spikes that were present on the output voltage and inductor current waveforms, the converter would be more useful.