PMP6025
TPS92411
120VAC Input, 3.5W Output LED Driver Candelabra (E12) and Small Form Factor LED Lightbulbs Test Report

TEXAS INSTRUMENTS

January 2, 2015

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1 Introduction

The TPS92411 reference design is an offline triac dimmable power factor corrected current regulator utilizing two TPS92411 floating switches for low cost and small form factor. The LED stack voltages are chosen at a 2:1 ratio to create 4 different operating states ranging from 00, all switches closed, to 11, all switches open. The power factor is above 0.9 and Total Harmonic Distortion is under 20%. The reference design uses no magnetics. Unlike other offline LED linear current regulators this design has energy storage to provide low light flicker and better LED utilization than non-energy storage designs.

2 Description

This reference design's input voltage range is 85-135 VAC, input power is 5 watts at 120 VAC. It is intended as a 40 watt incandescent replacement, over 400 lumens. The current level can be increased or decreased as desired. The current regulator is a discrete circuit that provides power factor correction and input line regulation. It uses 22 volt LEDs connected in series/parallel to create two LED stack voltages of 44 and 88 volts (they actually measure 81.2 and 40.7 volts). The design intention was low cost and small form factor. Efficiency can be increased by adding a third TPS92411 stage if desired, it would be a 22 volt section resulting in a 88/44/22 volt arrangement.

2.1 Typical Applications

This design purposely fits inside an E12 candelabra incandescent footprint as seen the photos below. It is a thin, 0.031", two section FR4 PCB with thermal copper spreading planes to allow heatsinking the LEDs and linear MOSFET. The two boards mount at 90 degrees via a six pin connector to fit in the E12 candelabra outline. It can be adjusted for higher or lower output power as needed.

2.2 Features

2.2.1 Feature description

This section describes certain features of the reference design board and some considerations of each.

2.2.1.1 Rsns pin

The Rsns pin tells the TPS92411 when to close its internal MOSFET bypassing the current going to its LED stack and energy storage capacitor. The internal current source is 4 uA and internal trip threshold is 0.210 volts. An 806 Kohm Rsns resistor will cause the TPS92411 to close as it crosses 3.0 volts from its common to the system common. The threshold voltage is set high enough to prevent the discrete current regulator from dropping out, it is the voltage headroom for the current regulator. It has a negative effect on efficiency if set too high and can cause interruptions in the power factor corrected current waveform and triac misfire if set too low. The Rsns pin functions as the voltage source to the TPS92411 is falling.

2.2.1.2 Rset pin

The Rset pin tells the TPS92411 when to open its internal MOSFET allowing current to flow to its LED stack and energy storage capacitor. It uses half the current through the Rsns resistor to create a voltage drop on the Rset resistor. As the voltage source to theTPS92411 rises the current in Rsns rises increasing the voltage drop on Rset. As the voltage on the Rset pin crosses an internal 1.25 volt threshold causing the TPS92411 MOSFET to open allowing current to flow to the LEDs and storage capacitor. The Rset pin functions as the voltage source to the TPS92411 is rising.

2.2.1.3 Slew controlled drain connection

This is the connection to the drain of internal MOSFET that allows the TPS92411 to bypass its LED section, MOSFET closed, or allows the current to power its LED stack and charge the energy storage capacitor, MOSFET open. The MOSFET state is set by the Rsns and Rset thresholds via an internal RS latch. The drain connection is slew rate controlled to reduce conducted EMI. The MOSFET also closes faster than it opens to prevent the current regulator from dropping out when two or more TPS92411s are switching.

2.2.1.4 Over Voltage Protection

The TPS92411 used on this design has built in over voltage protection. If the LED section opens the current regulator will continue to charge the energy storage capacitor beyond the LED section voltage. When the voltage on Vin reaches 100 volts the TPS92411 closes bypassing the open LED section. As the energy storage capacitor discharges to 96 volts the TPS92411 will open again until reaching the 100 volt threshold. The hysteresis is four volts.

2.2.1.5 Power factor correction

A simple discrete current regulator using a MOSFET, Q1, current sense resistor, R13, and a transistor, Q2 regulates current from the rectified AC. The reference to this regulator is a resistor divider from rectified AC, R8 and R11. Note that Q2 collector and emitter are in this divider but it is a fixed DC voltage, the Vgs threshold of Q1 plus the Vbe of Q2. The Vgs is small compared to the rectified AC voltage so it will have little effect on power factor. The Vbe drop of Q4 will add some DC offset which helps with triac dimming.

2.2.1.6 Line regulation

The TPS92411 reference design uses a simple zener/resistor circuit that pulls up on the base of Q2 as the input voltage rises above 160-165 volts. This kicks in around 120 VAC. Lowering the zener voltage of D9 and D12 will allow this to kick in at a lower input voltage however it compromises power factor and THD. Note that R13 and possibly R9 will have to be adjusted if lower voltage zener diodes are used. Other reference designs using the TPS92411 and/or the TPS92410 have alternate line regulation schemes, this was used to be the least expensive and can be removed if not needed.

2.2.1.7 EMI control

A capacitor, C7, across the discrete current regulator MOSFET gate to source, Q1, along with the TPS92411 slew control allows the reference design to pass QP conducted EMI with 2.7dB of margin with only a 0.033 uF capacitor, C2, across rectified AC. Radiated EMI is not an issue with this topology. The EMI capacitor value is proportional to the input current. Doubling the power would require doubling the capacitor value, C2. The triac damper capacitor would also need to double.

3 Electrical Performance Specifications

Table 1: TPS92411 discrete linear Electrical Performance Specifications

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNITS
Input Characteristics					
Voltage range	Normal operation	100	120	120	V
Voltage range	Maximum range	85		135	V
Maximum input current	At 120 Vrms input		0.050		A rms
Input power			5	6	watts
Output Characteristics					
Output voltage, stack 1 (top)	Nominal		81.2		V
Output voltage, stack 2	Nominal		40.7		V

4 Schematic

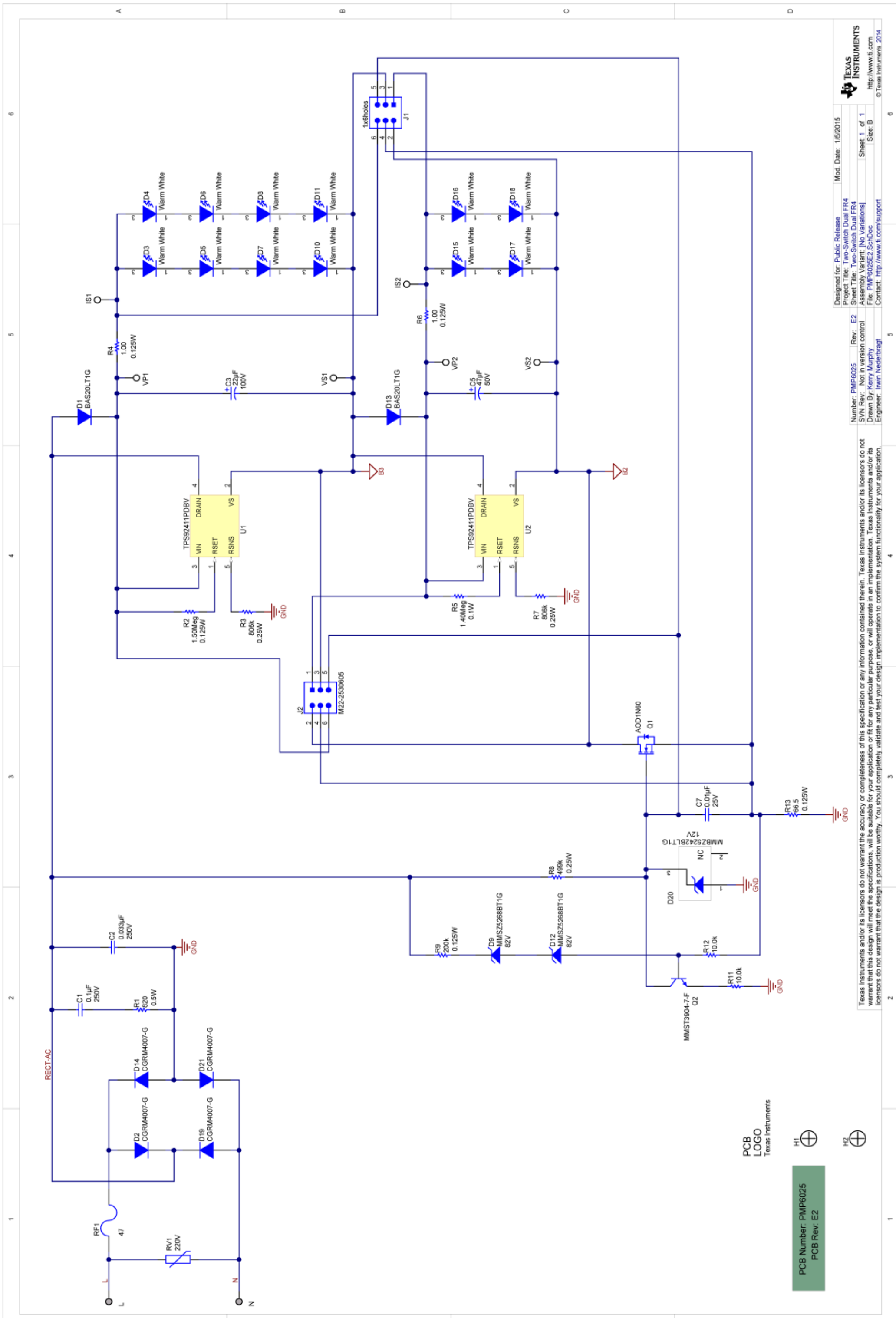

Figure 1: TPS92411 discrete linear Schematic

5 Performance Data and Typical Characteristic Curves

Figures 2 through 22 present typical performance curves for TPS92411 discrete design.

5.1 Efficiency

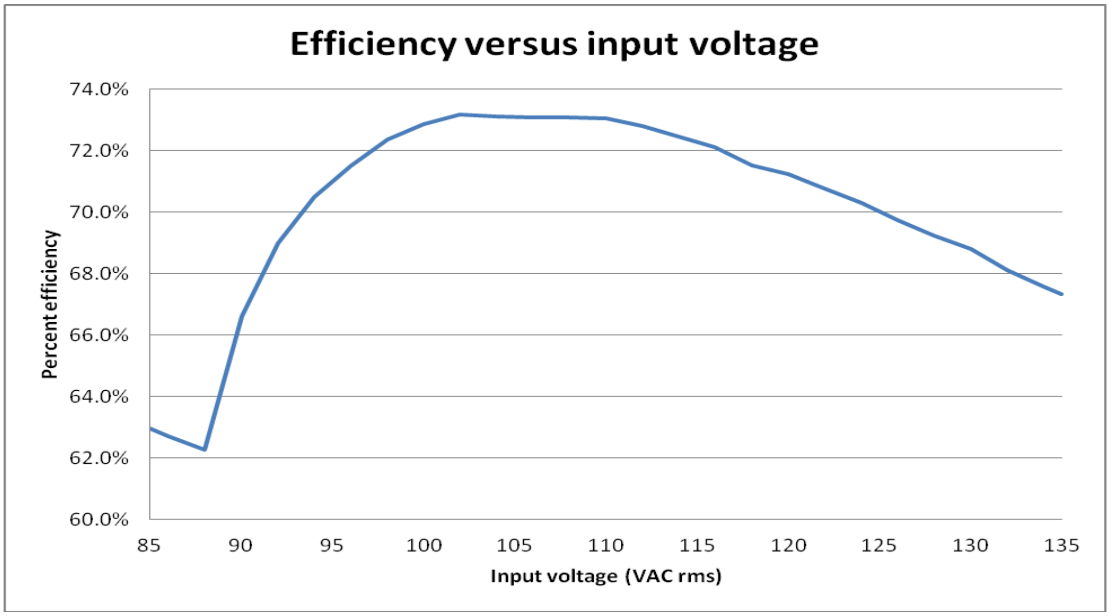

Figure 2: Efficiency

5.2 Line Regulation

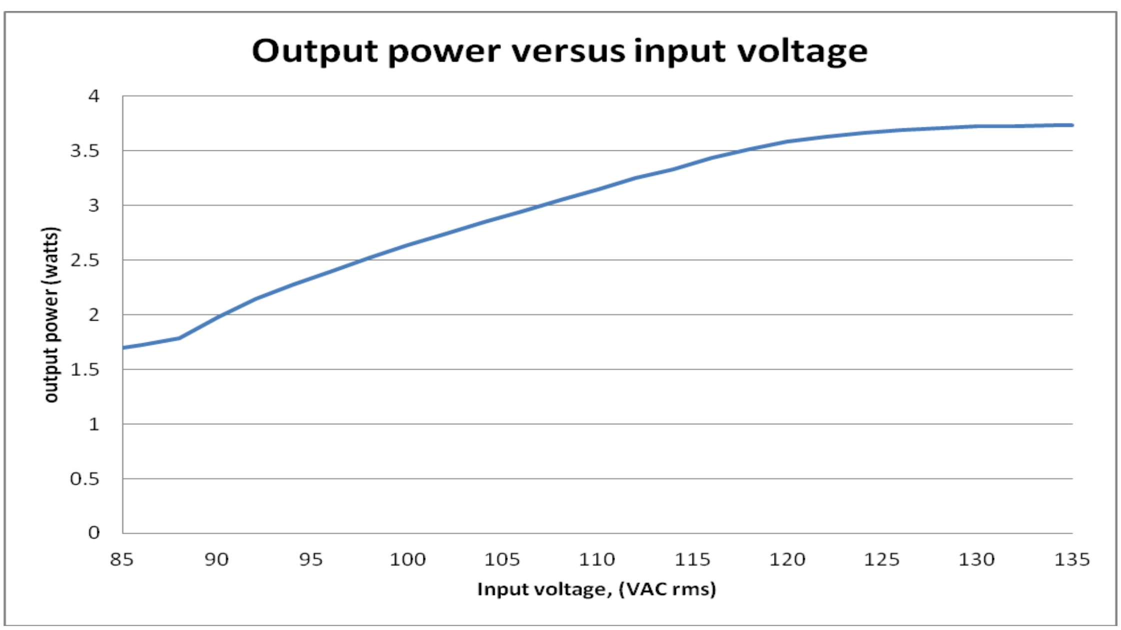

Figure 3: Line Regulation, kicks in at approximately 120 VAC

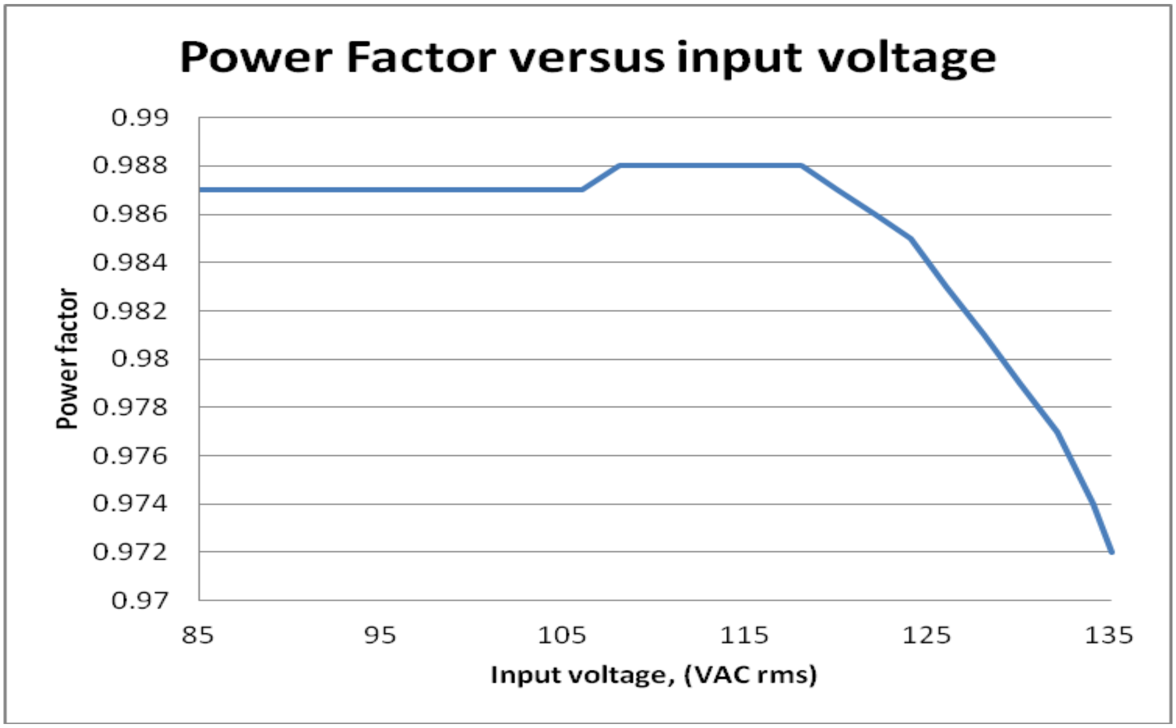

Figure 4: Power factor correction at 60 Hz, PF starts dropping off as line regulation circuit kicks in

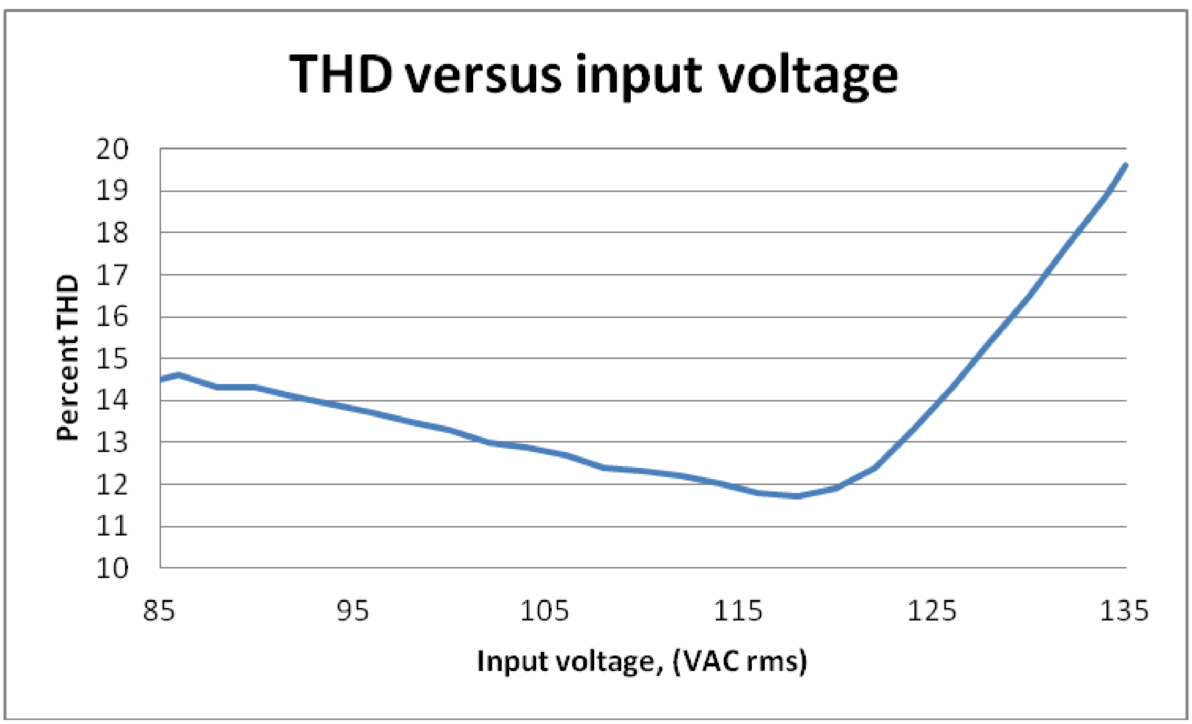

Figure 5: Total Harmonic Distortion at 60 Hz, THD increases as line regulation circuit kicks in

5.3 Drain voltage of current regulator

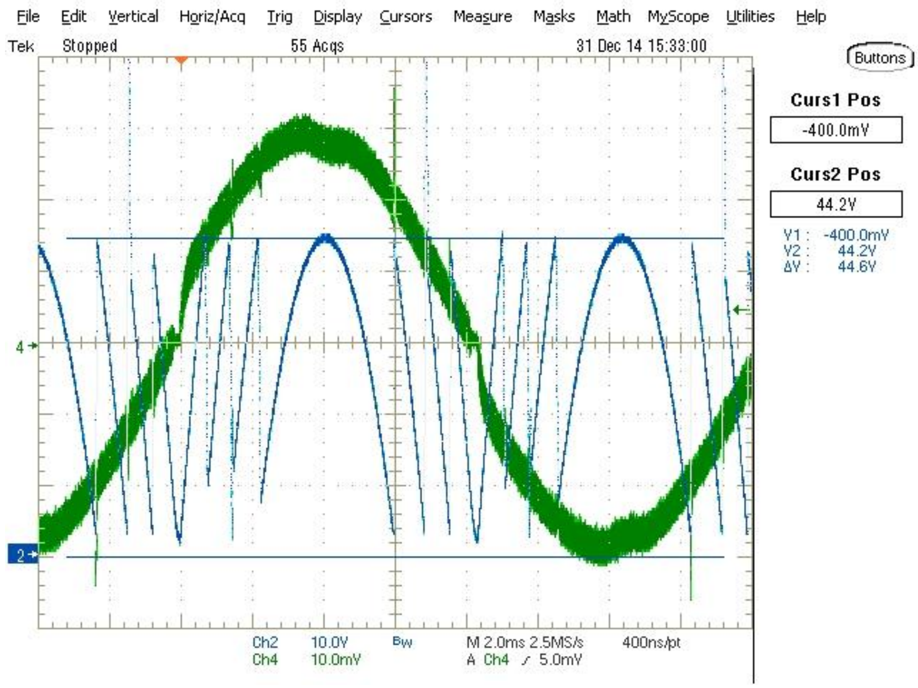

Figure 6: Current regulator drain waveform (Blue), input current (green)

5.4 Current sense (MOSFET source and gate signals)

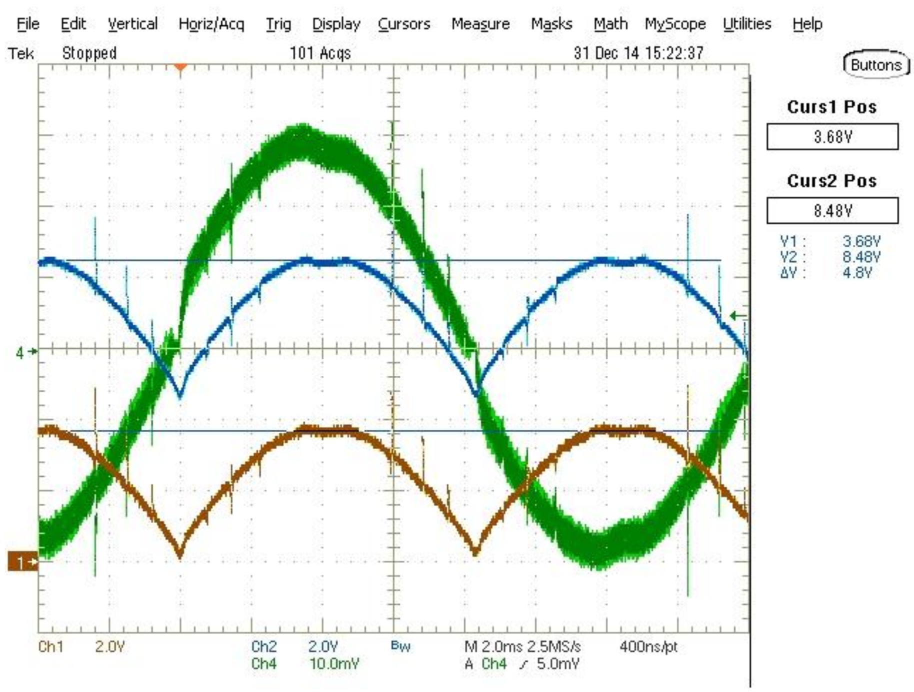

Figure 7: Voltage at current sense resistor, R13 (Brown), Q1 MOSFET gate (blue)

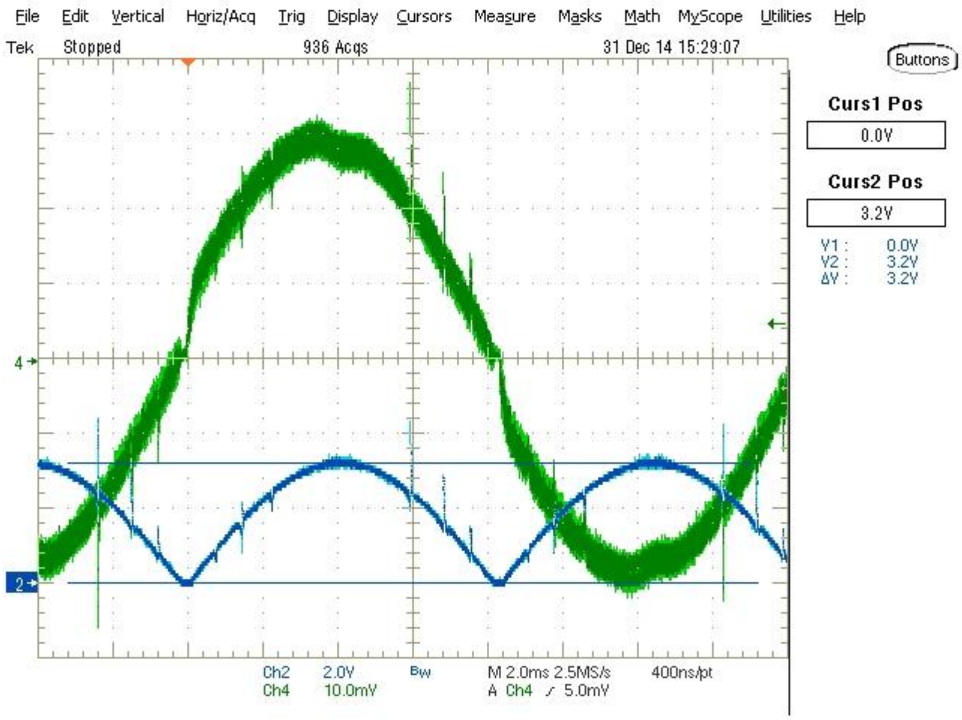

Figure 8: PFC command, R11 voltage (blue)

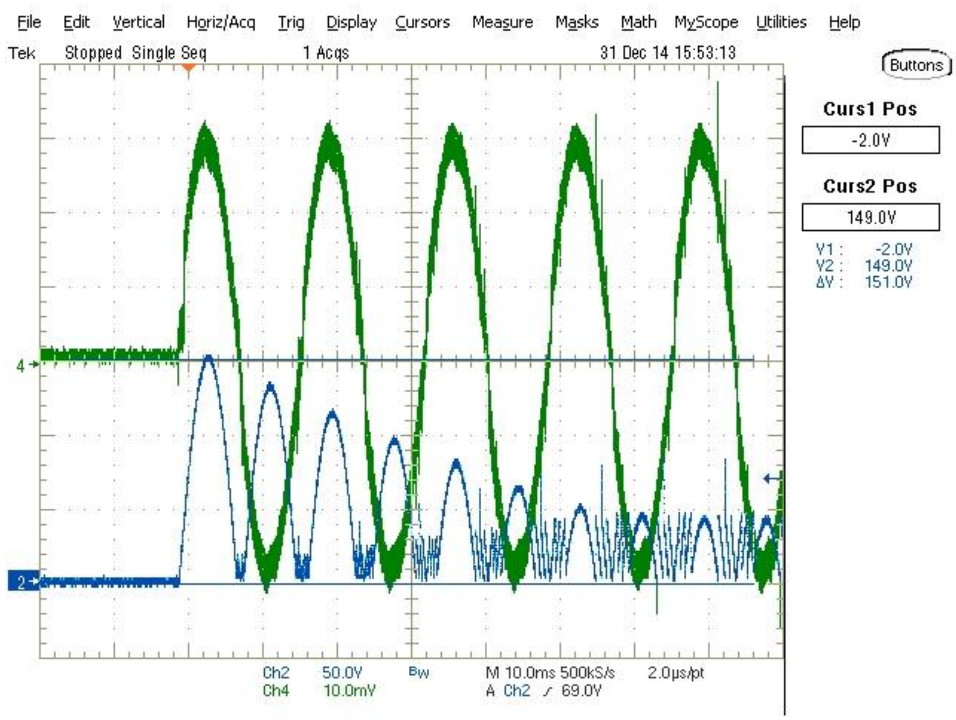

Figure 9: Current regulator drain voltage during power on (blue), energy storage capacitors charging, current from AC line (green), about seven half cycles to charge LED section capacitors (light delay from turn on)

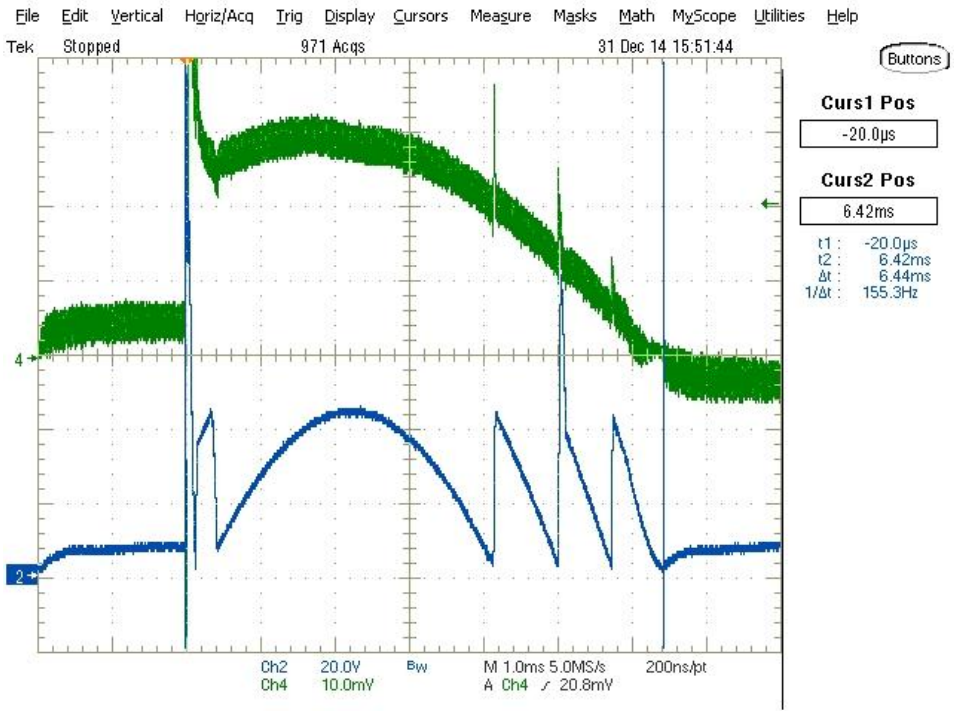

Figure 10: Current regulator drain voltage when forward phase dimming (dimmer at maximum)

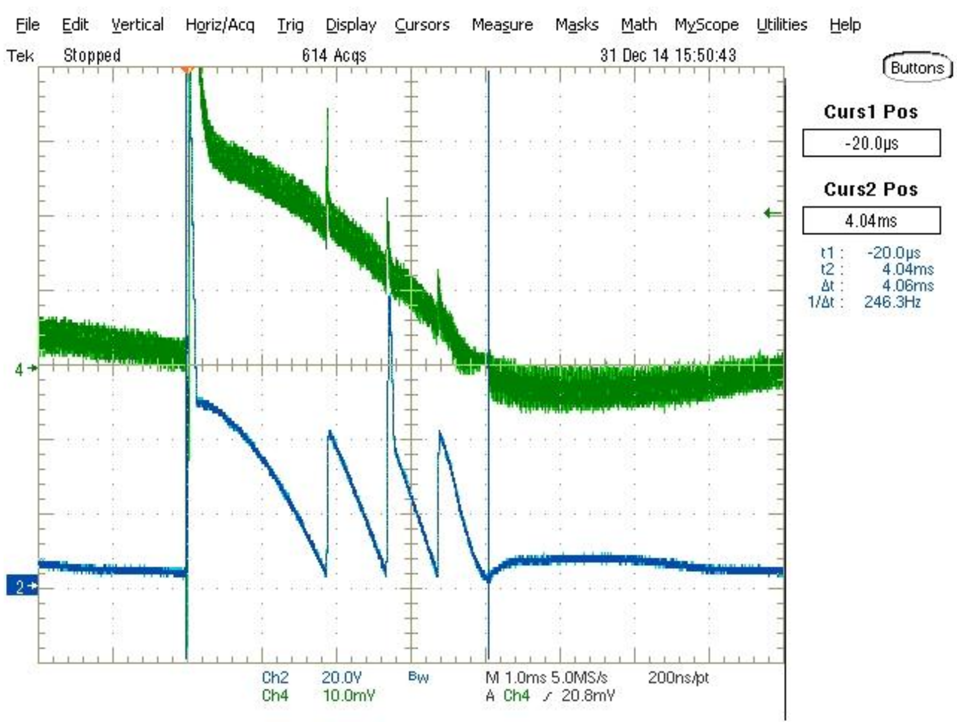

Figure 11: Current regulator drain voltage when forward phase dimming (dimmer set to peak of rectified AC)

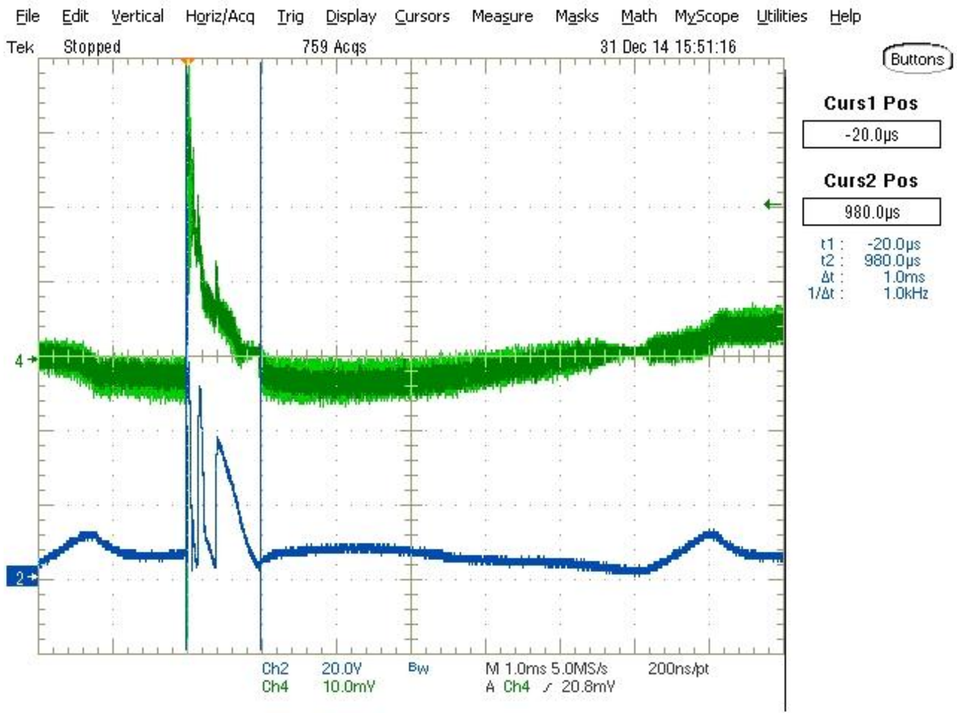

Figure 12: Current regulator drain waveform when forward phase dimming (dimmer set to minimum)

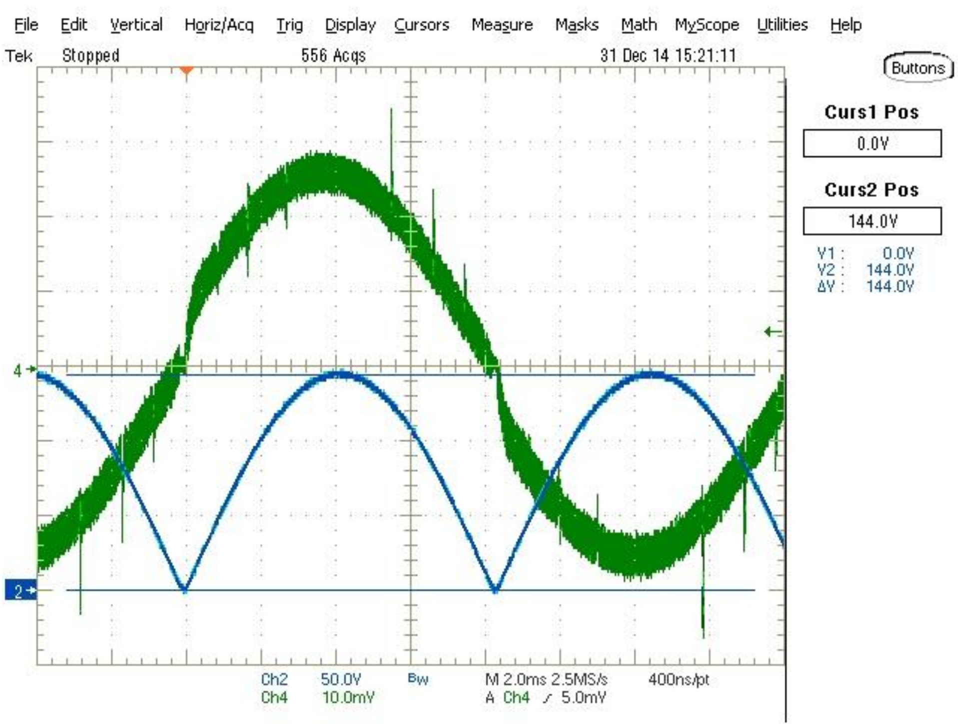

Figure 13: Input current waveform at 105 VAC, no line regulation present, rectified AC (blue)

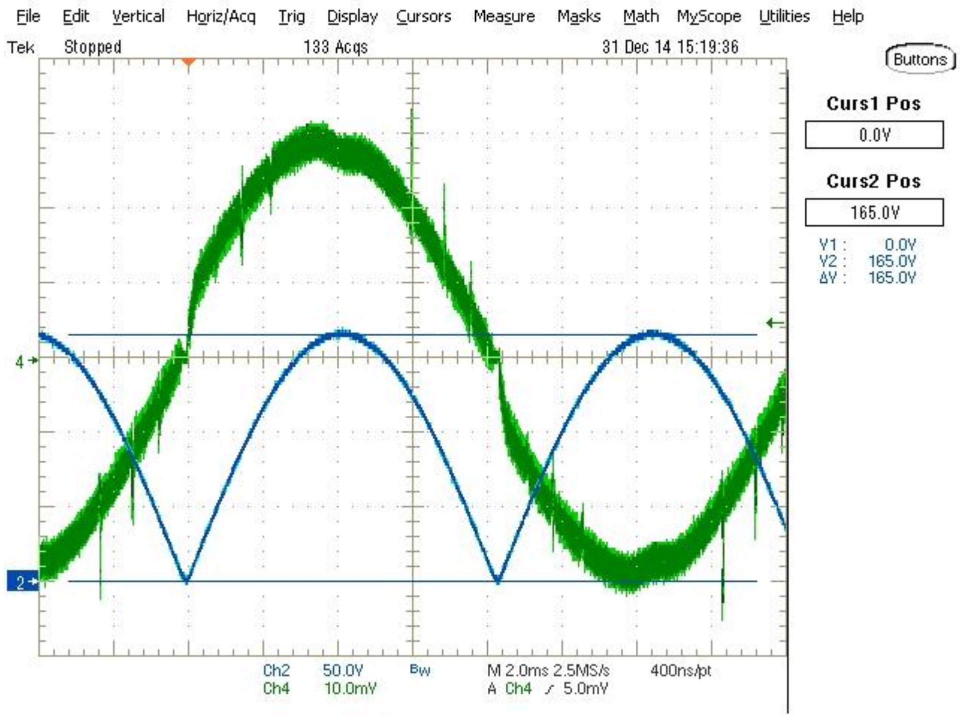

Figure 14: Input current waveform at 120 VAC, line regulation circuit just starting to reduce peaks, rectified AC (blue)

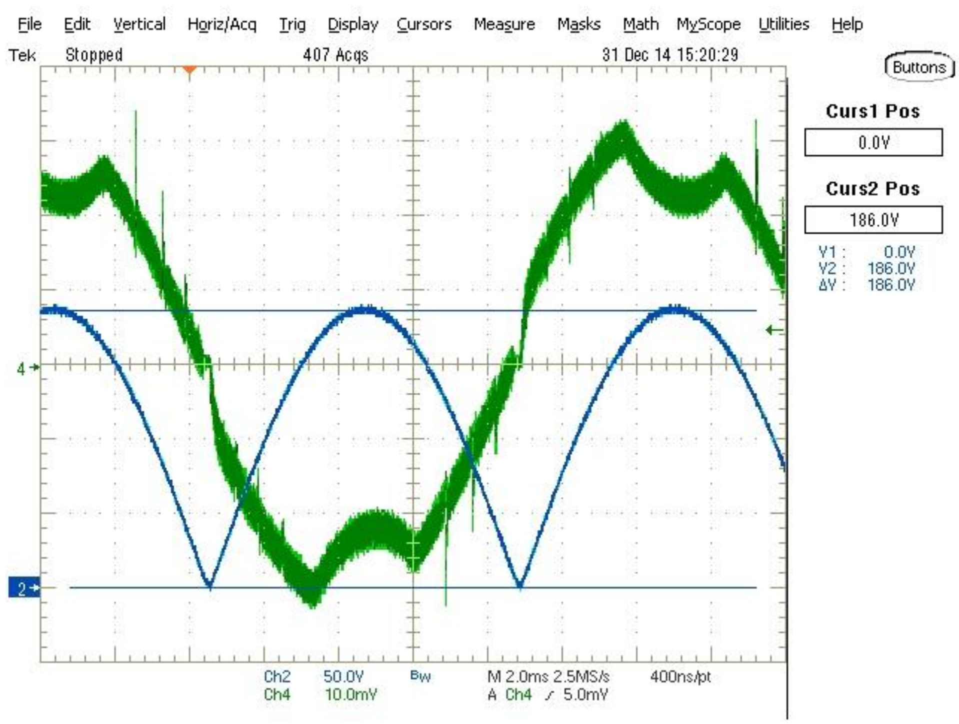

Figure 15: Input current waveform at 135 VAC, line regulation circuit reducing peaks, rectified AC (blue)

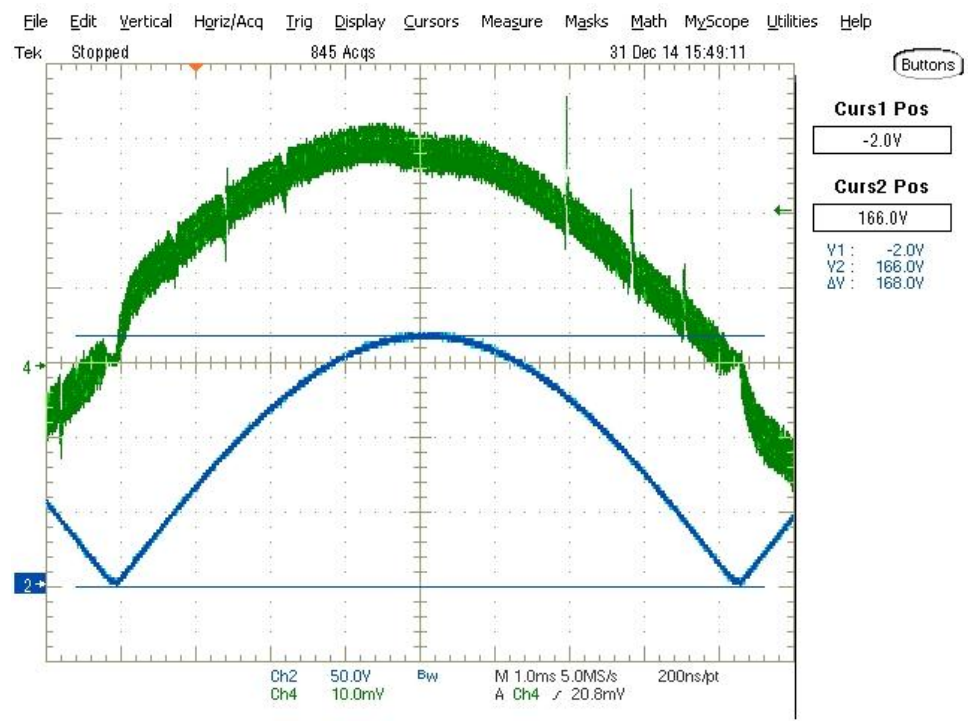

Figure 16: Rectified AC, reference for next oscilloscope plots (blue)

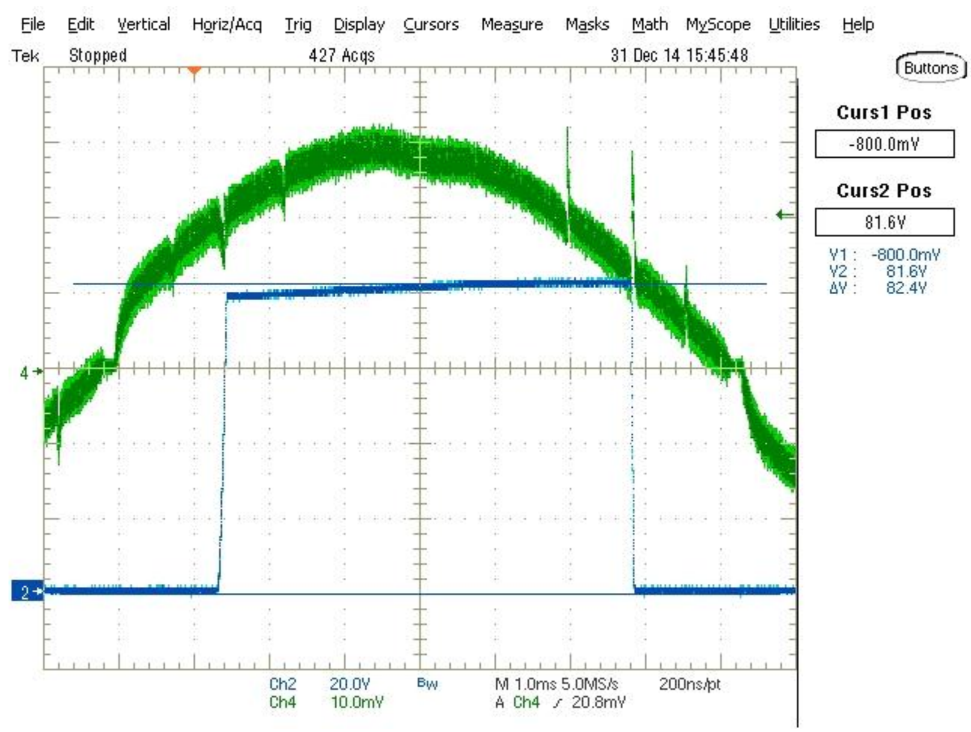

Figure 17: Upper TPS92411, U1, drain waveform, U1 opens approximately 85 volts (rising), and closes approximately 85 volts (falling)

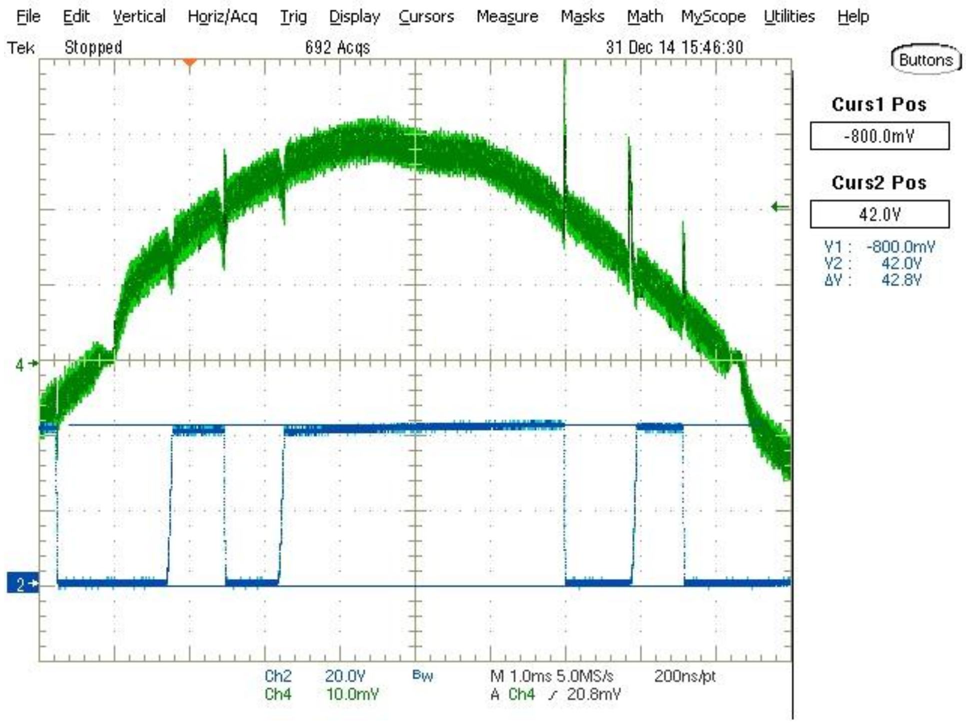

Figure 18: Lower TPS92411, U2, drain waveform, opens approximately 45 volts, closes at approximately 85 volts when U1 opens and opens again at approximately 125 volts, all as line voltage is rising. Reverse order as line voltage falls

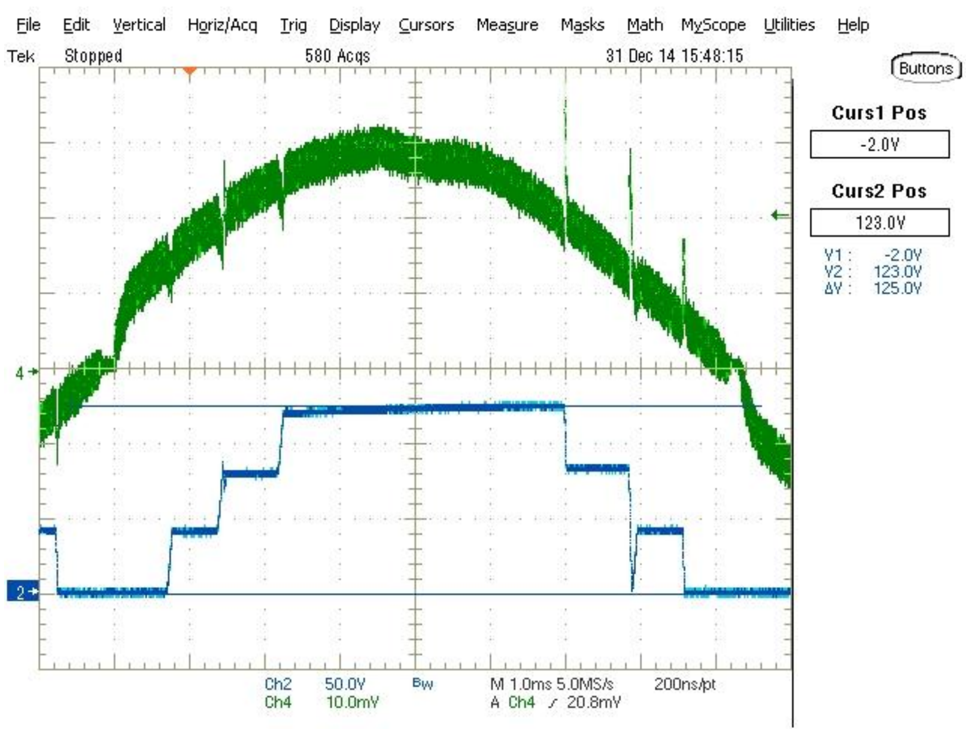

Figure 19: Series load voltage, sum of the LED stacks as the input voltage rises and falls

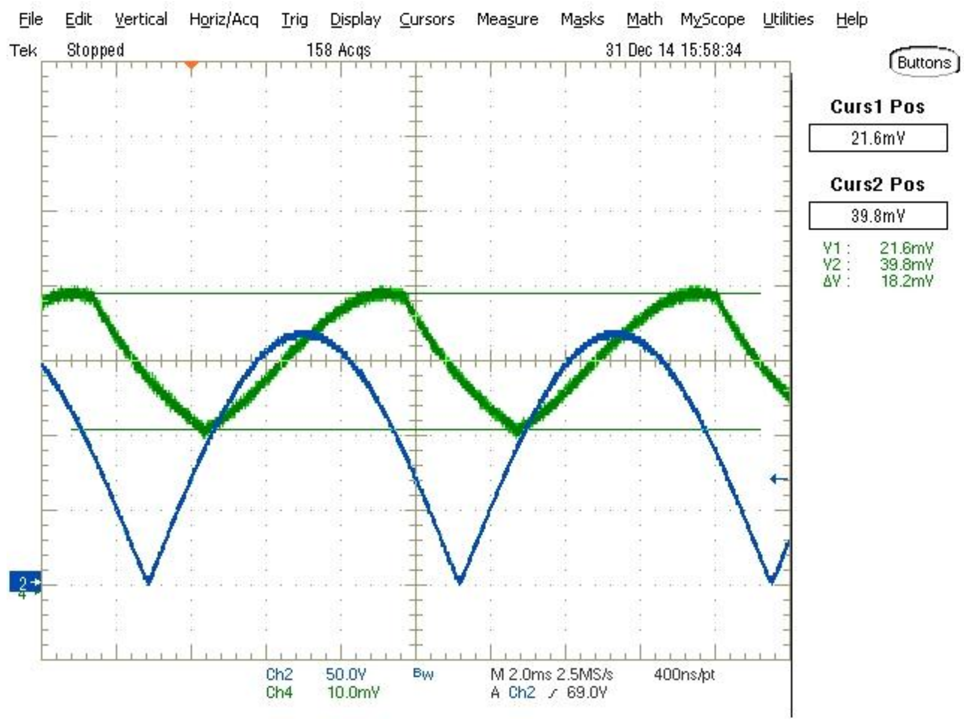

Figure 20: current ripple stack 1, 80 volt, current probe 10 mA/division, approximately 41% peak to peak over average current ripple. Increasing C3 reduces this proportionally

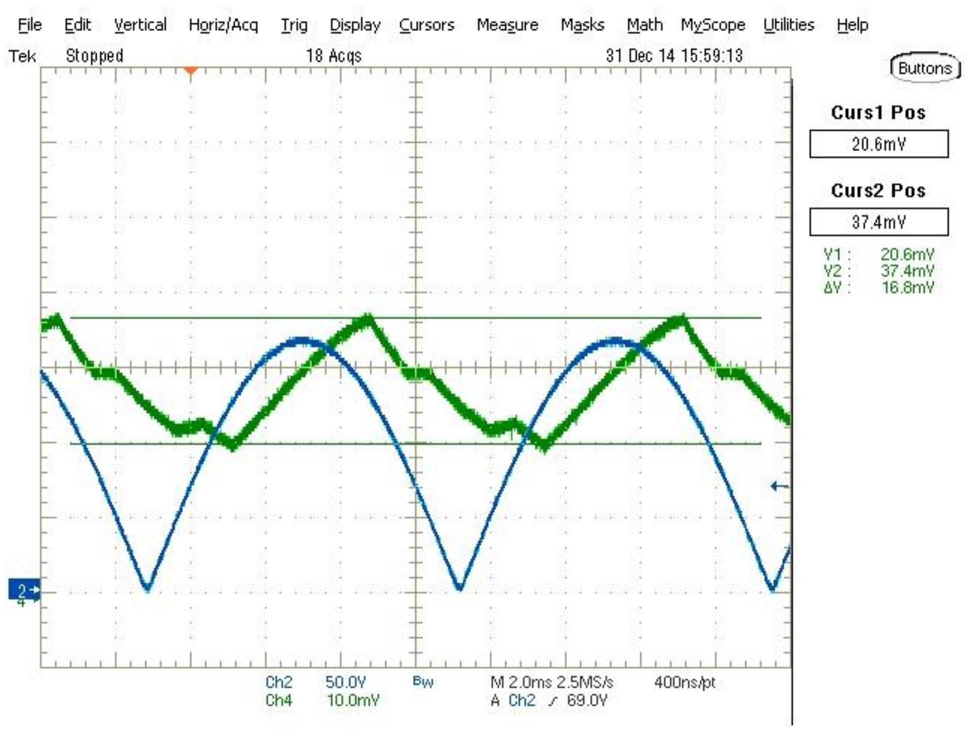

Figure 21: current ripple stack 2, 40 volt, current probe 10 mA/division, approximately 42% peak to peak over average current ripple, Increasing C5 reduces this proportionally

5.5 EMI Performance

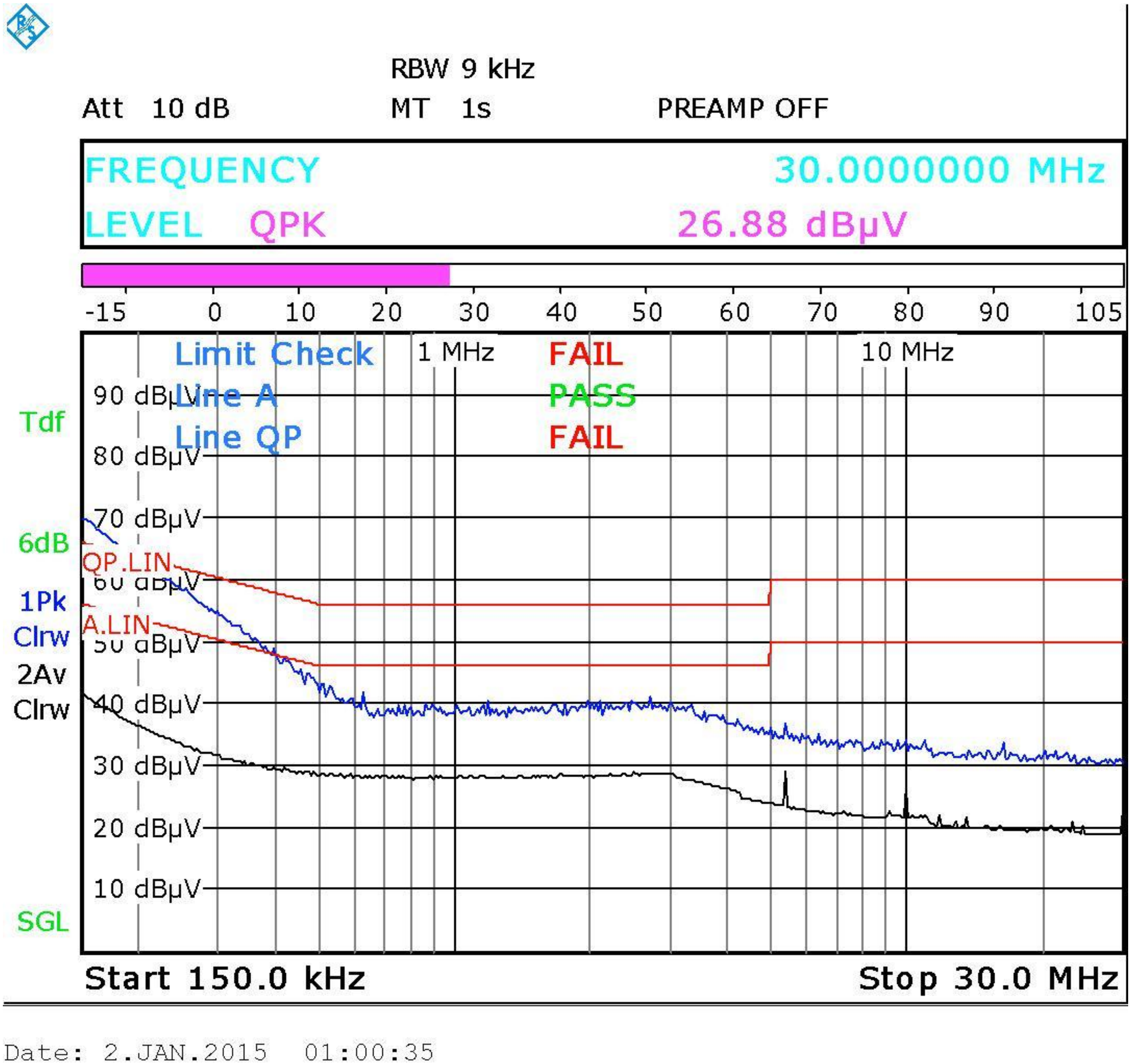

Figure 22: Conducted EMI scan peak and average, Quasi-peak measures -2.7 dB for both line and neutral at 150 KHz

5.6 TPS92411 test hardware, designed mounting to heatsink though printed circuit board, 0.031" thick.

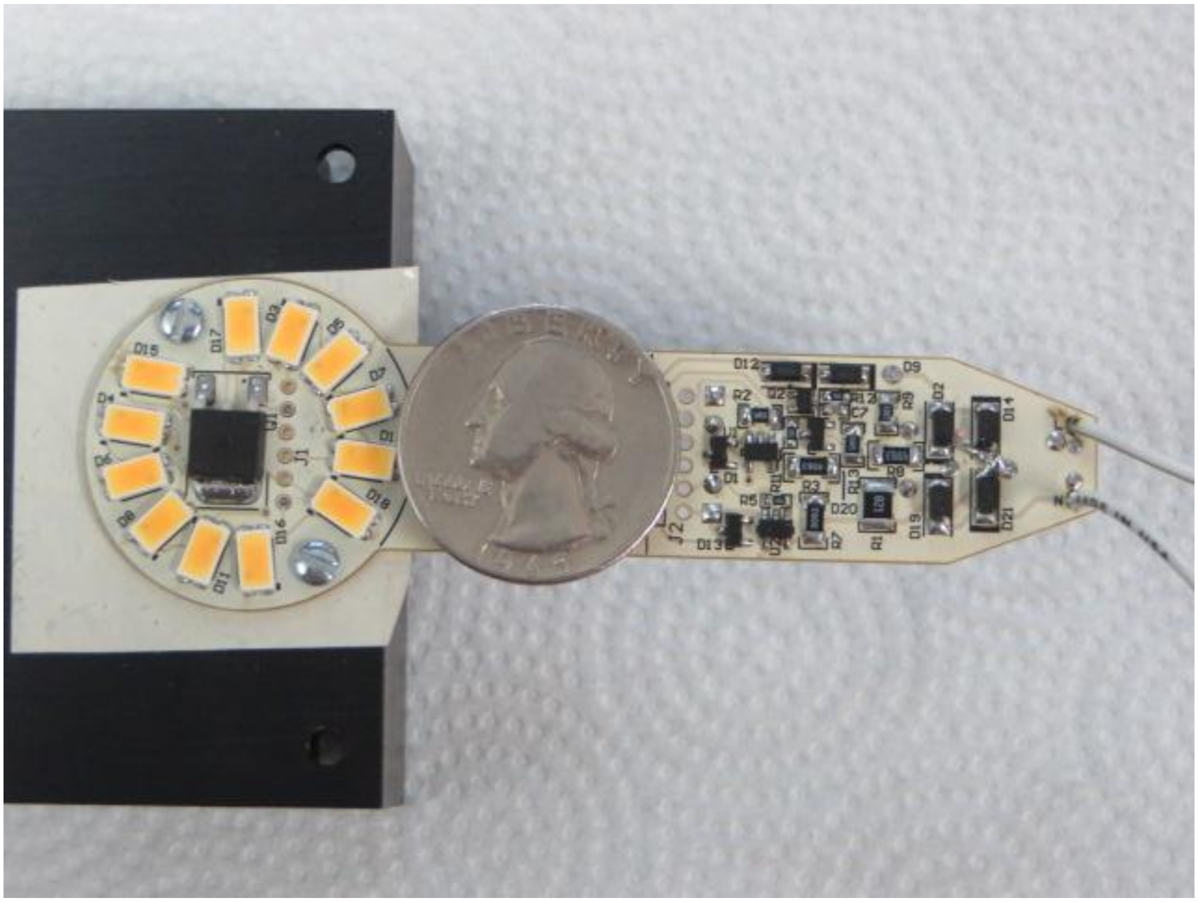

Figure 23: PCB section where quarter is at is removed when installed in candelabra, J2 solders to J1 with a right angle connector, all hot components on round board that is connected to heatsink

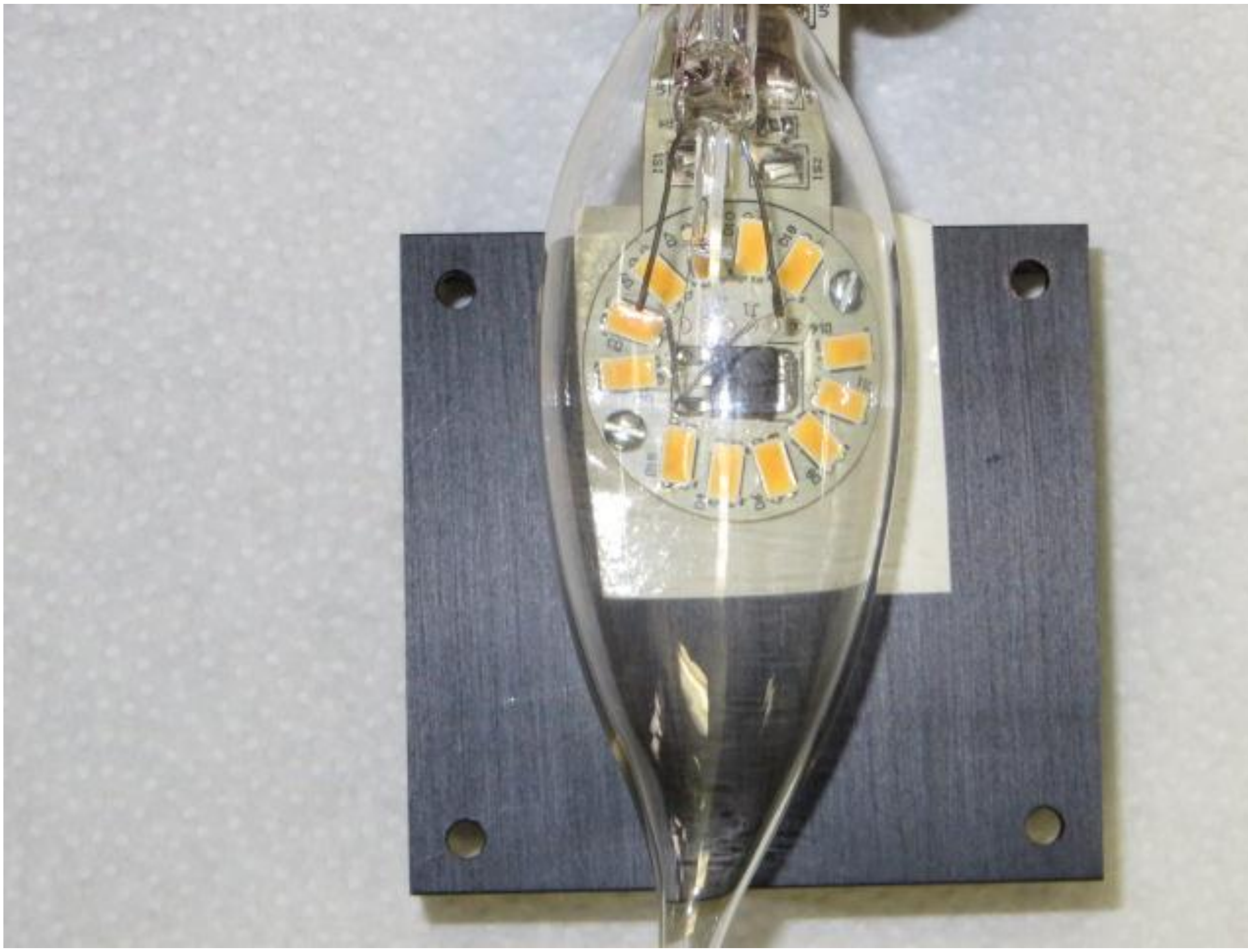

Figure 24: Incandescent candelabra reference, LED board fits inside, PCB rotates 90 degrees when inside candelabra bulb

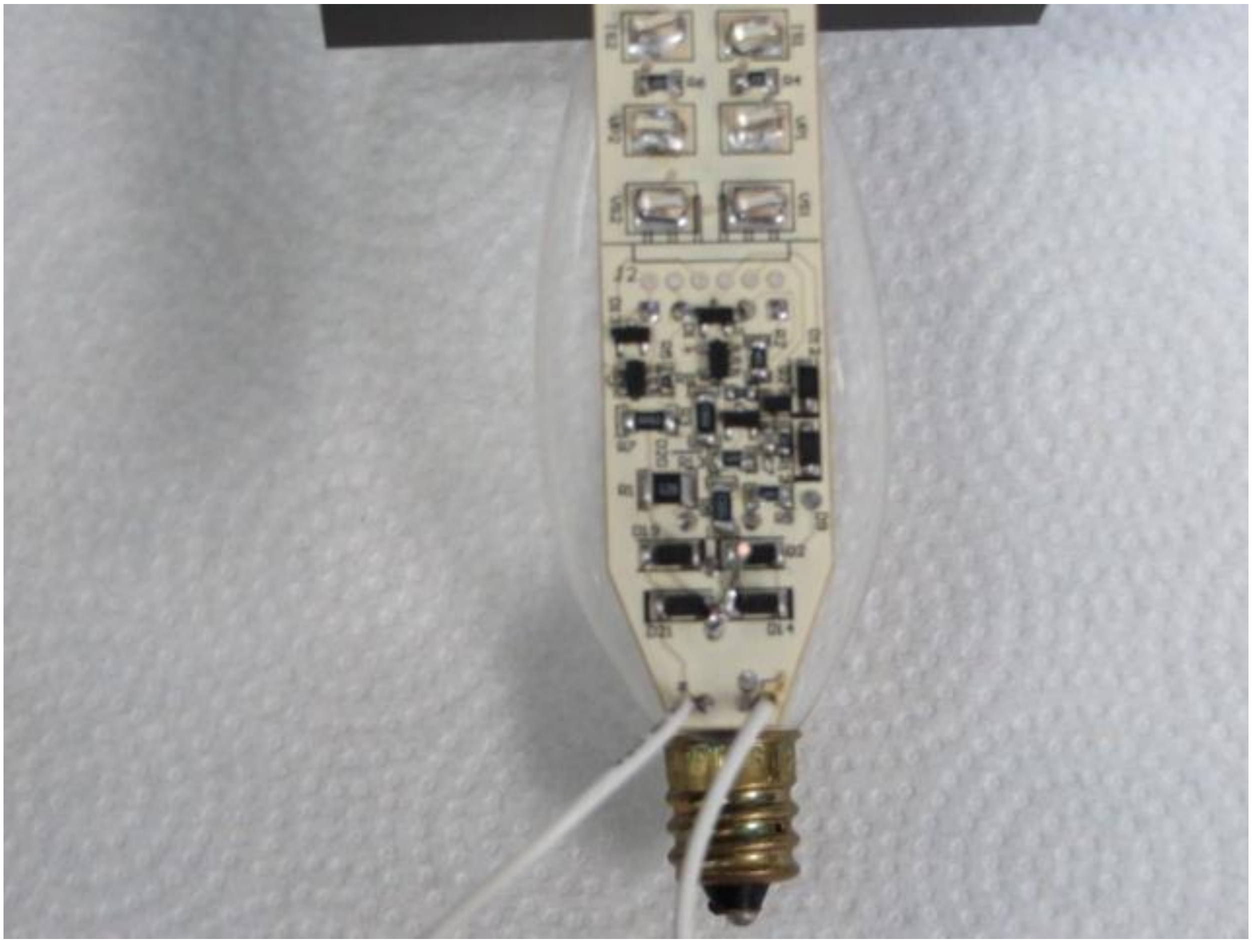

Figure 25: SMT and through hole components reside in base portion of E12 candelabra, narrow to leave room for heatsink material for round portion of PCB

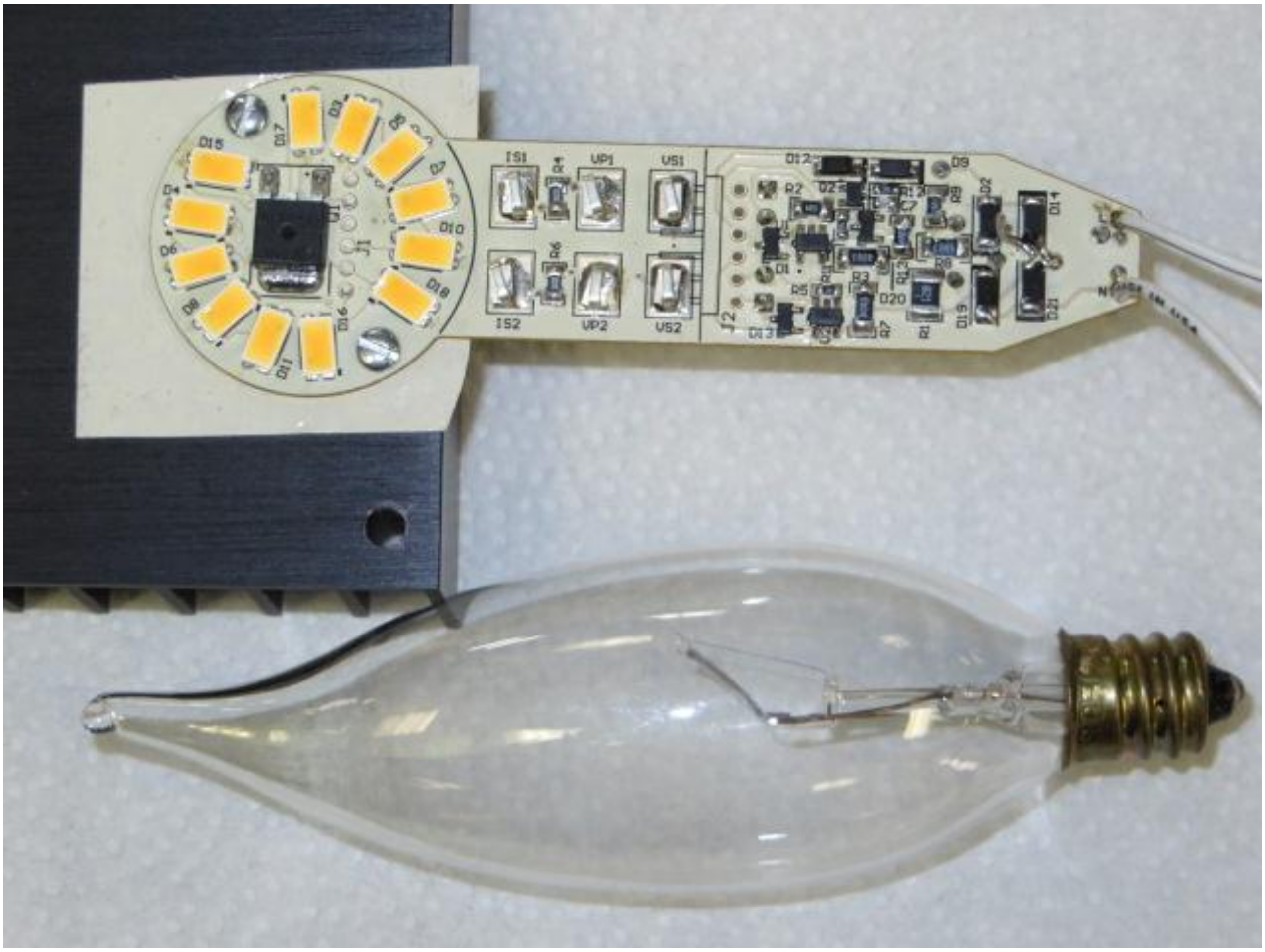

Figure 26: side by side with incandescent E12 candelabra, test point section of PCB is removed (test points used for measuring string voltages and currents.

6 TPS92411 Reference Design PCB layout

The following figures (Figure 27 through Figure 28) show the design of the TPS92411 printed circuit board.

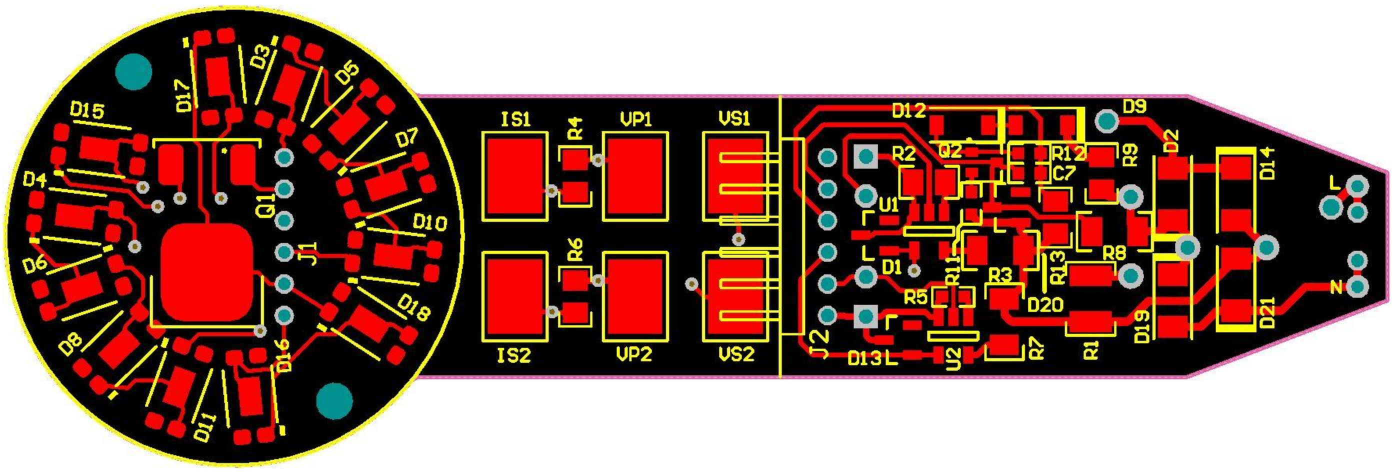

Figure 27: Top Layer and Top Overlay (Top view)

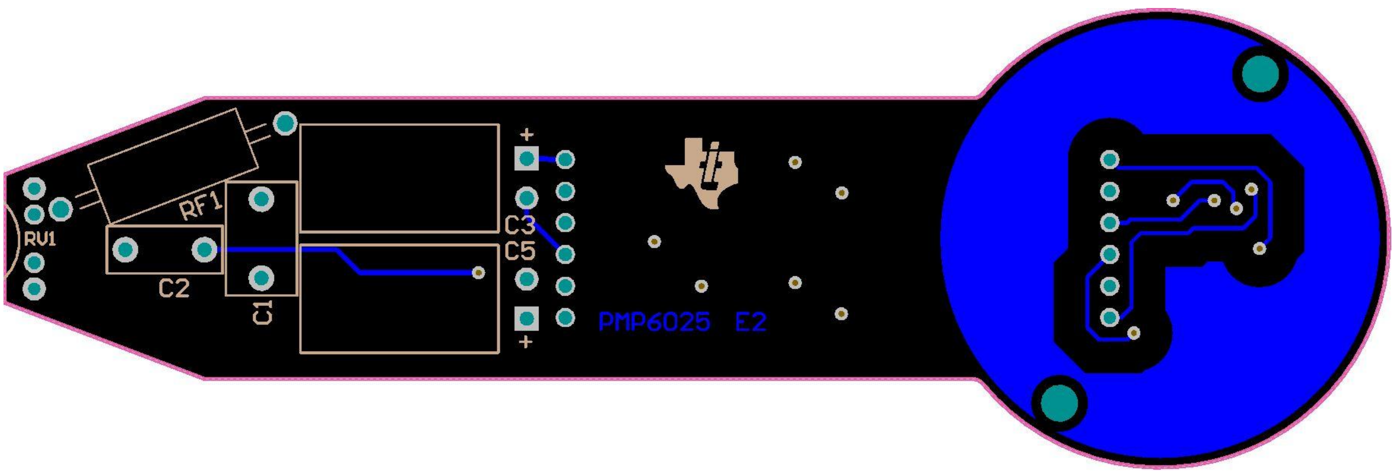

Figure 28: Bottom Layer and Bottom Overlay (Bottom view)

7 Bill of Materials

Table 2: The TPS92411 discrete linear components list according to the schematic shown in Figure 1

Dsgr	Qty	Value	PartNumber	Mfgr	Description	Size
C1	1	0.1µF	R82IC3100DQ60J	Kemet	CAP, Film, 0.1uF, 250VDC, Radial	Radial
C2	1	0.033µF	B32529C3333K	EPCOS Inc	CAP, Film, 0.033uF, 250VDC, Radial	Radial
C3	1	22µF	UVZ2A220MED	Nichicon	CAP, Alum, 22uF, 100V, +/-20%, Radial	Radial, Can
C5	1	47µF	UVZ1H470MED	Nichicon	CAP, Alum, 47uF, 50V, +/-20%, Radial	Radial, Can
C7	1	0.01uF	C1608C0G1E103 J	TDK	CAP, CERM, 0.01uF, 25V, +/-5%, C0G/NP0, 0603	0603
D1, D13	2	1.25V @ 200mA	BAS20LT1G	ON Semi	Diode, Switch, 200V, 0.2A, SOT-23	TO-236-3, SC-59, SOT-23-3
D2, D14, D19, D21	4	1000V	CGRM4007-G	Comchip	Diode, P-N, 1000V, 1A, 3.9x1.7x1.8mm	3.9x1.7x1.8mm
D3, D4, D5, D6, D7, D8, D10, D11, D15, D16, D17, D18	12	Warm White	SAW8KG0B-X8Y1-HA	Seoul Semi	LED SMD WARM WHITE 2700K	3x.75x5.2mm
D9, D12	2	900mV @ 10mA	MMSZ5268BT1G	ON Semi	Diode, Zener, 82V, 500mW, SOD-123	SOD-123
D20	1	12V	MMBZ5242BLT1G	ON Semi	Diode, Zener, 12V, 225mW, SOT-23	SOT-23
IS1, IS2, VP1, VP2, VS1, VS2	6	SMT	5016	Keystone	Test Point, Compact, SMT	Testpoint_Keystone_ Compact
J1	1	1x6holes		Harwin Inc	1x6 Hole Pattern	1x6 Header
J2	1		M22-2530605	Harwin Inc	SIL VERTICAL PC TAIL PIN HEADER	1x6 Header
Q1	1		AOD1N60	Alpha & Omega Semicond uctor Inc	MOSFET, N-CH, 600V, 1.3A, DPAK	TO-252-3, DPak (2 Leads + Tab), SC-63
Q2	1	0.3V	MMST3904-7-F	Diodes Inc.	Transistor, NPN, 20V, 0.2A, SOT-323	SOT-323
R1	1	820	CRCW1210820RJ NEA	Vishay Dale	RES, 820 ohm, 5%, 0.5W, 1210	1210 (3225 Metric)
R2	1	1.50Meg	CRCW08051M50 FKEA	Vishay-Dale	RES, 1.50Meg ohm, 1%, 0.125W, 0805	0805

R3, R7	2	806k	CRCW1206806KFKEA	Vishay-Dale	RES, 806k ohm, 1%, 0.25W, 1206	1206
R4, R6	2	1.00	RMCF0805FT1R00	Stackpole Electronics Inc	RES, 1.00 ohm, 1%, 0.125W, 0805	0805
R5	1	1.40Meg	CRCW06031M40FKEA	Vishay-Dale	RES, 1.40Meg ohm, 1%, 0.1W, 0603	0603
R8	1	499k	CRCW1206499KFKEA	Vishay-Dale	RES, 499k ohm, 1%, 0.25W, 1206	1206
R9	1	200k	CRCW0805200KFKEA	Vishay-Dale	RES, 200 k, 1%, 0.125 W, 0805	0805
R11, R12	2	10.0k	CRCW060310K0FKEA	Vishay-Dale	RES, 10.0k ohm, 1%, 0.1W, 0603	0603
R13	1	66.5	CRCW080566R5FKEA	Vishay-Dale	RES, 66.5, 1%, 0.125 W, 0805	0805
RF1	1	47	EMC2-47RKI	TT Electronics/IRC	RES, 47, 10%, 2 W, Fusible, TH	Axial resistor
RV1	1	220V	ERZ-V05D221	Panasonic	Varistor, 220V, 600A, TH	Disc 10x7mm
U1, U2	2		TPS92411PDBV	Texas Instruments	Switch Controlled Direct Drive Switch for Offline LED Drivers, DBV0005A	DBV0005A