PMP6021
Fault Protected 230 VAC In / 17W Output LED Driver Using No Magnetic Components Test Report

December 05, 2014

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1 Introduction

The TPS92410/TPS92411 reference design is a triac dimmable power factor corrected current regulator driving four LED sections with energy storage to reduce flicker. The design is approximately 20 watts input power and will be around 2000 lumens dependent on the LEDs used. The TPS92410 controls the current through the MOSFET to achieve excellent power factor and line regulation with its internal multiplier. The TPS92410 has a unique circuit to detect triac rising edges and will change the current reference to DC instead of sinusoidal to provide enough holding current to satisfy the triac dimmer. The TPS92411s are used to sense when to bypass their LED section or allow current to flow to it and the storage capacitor. The LED sections are arranged to be near an 8-4-2-1 ratio to optimize the 16 switch states during a half line cycle.

2 Description

This reference design's input voltage range is 200-265 VAC, input power is 20 watts at 230 VAC. The current regulator is the TPS92410 that provides power factor correction, input line regulation via a multiplier and a triac dimmer detect function that switches to a DC current reference to prevent triac dimmer misfire. It uses 6 volt LEDs connected in series to create four LED stack voltages of 18, 36, 78 and 168 volts. This is not exactly an 8:4:2:1 ratio, it was optimized for efficiency over the input voltage range. The design is also optimized for efficiency while still enabling triac dimming. The upper 168 volt stack uses an external cascode arranged external MOSFET to allow the TPS92411 to bypass a string voltage above 100 volts and control turn-on and turn-off slew rates for EMI control. There is open LED protection with the TPS92410/TPS92411 design that causes the LED string to be bypassed and force the TPS92410 will go into a low current mode to prevent excess power dissipation in the current regulator MOSFET. The design achieves 87% efficiency.

2.1 Typical Applications

This design is suitable recessed lighting, can lights or other LED lighting applications with 230 VAC input. It can be adjusted to other input voltage levels by adjusting the number of LEDs. It can be adjusted for higher or lower output power as well.

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 TPS92411 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 TPS92411 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 it crosses an internal 1.25 volt threshold it trips a comparator 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 TPS92411 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 TPS92410/TPS92411 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 reaches 100 volts the TPS92411 closes bypassing the open LED section. As the energy storage capacitor discharges the TPS92411 will open again until reaching the 100 volt threshold. The hysteresis is four volts. When the TPS92411 is in the mode it is bypassing the LED section a majority of the time. The only discharge current is the TPS92411 operating current, approximately 200 uA.

If one or more of the LED sections are bypassed the average voltage on the current regulator MOSFET drain will be higher. The TPS92410 uses a resistor divider with a filter capacitor to average the MOSFET drain current. If the scaled down voltage exceeds 1.5 volts on the TPS92410 DOV pin it will trip Over Voltage Protection which scales back the LED current to 15% of nominal. This prevents the current regulator MOSFET from excess power dissipation. Note that the forward voltage of the LEDs will drop with lower operating current possibly creating an OVP latch condition meaning the power may need to be cycled to recover once the LED section has reconnected.

2.2.1.5 TPS92410 Power factor correction

The TPS92410 requires a resistor divider for the multiplier pin. This controls the current reference to the error amplifier. It causes the current waveform to follow the rectified AC waveform to achieve excellent power factor. The multiplier also compensates for line voltage so scaling the divider within its operating range will not affect output power.

2.2.1.6 TPS92410 Line regulation

The multiplier input to the TPS92410 allows the current reference to stay constant over an input voltage range such as 200-265 VAC as in this design.

2.2.1.7 TPS92410 Leading edge dim detect and DC offset

A patented leading edge dim detect circuit uses two pins, CPS and CDD. CPS sets a time per cycle to charge CDD at a fixed current. If a high slew rate (dv/dt) is detected on the multiplier pin CPS is activated and allows a current source to add charge to CDD capacitor. The CPS capacitor determines how long the pulse is per ½ line cycle. The CDD capacitor value determines how many cycles are needed to trip the internal 1.5 volt threshold causing the current reference to go from power factor corrected to a DC reference. The DC reference allows the current to continually flow through the triac dimmer preventing drop out (triac misfire) due to insufficient triac holding current. This is a latched mode, once a leading edge dimmer is detected it remains in DC reference mode until the power is cycled. Sensitivity to noise is controlled be CPS and CDD values as well as the voltage amplitude on the multiplier pin.

2.2.1.8 TSNS and ADIM

The TPS92410 has two control inputs for external circuitry use, the Analog Dim input and Thermal sense input. The two inputs are identical with one exception, ADIM has a turn-off function when pulled below 20 mV. The ADIM and TNS pins linearly reduced the current reference from 1.5 volts to zero. This reference design does not use the ADIM pin so it is pulled up to the 3.0 volt reference with a 200 Kohm resistor. The TSNS pin has a pull-up resistor to the reference and a 470 Kohm NTC thermistor to ground. This is used for thermal foldback. As the temperature rises and the NTC thermistor resistance crosses 30.1 Kohms the current reference will drop below 1.5 volts, reducing the overall power draw from the line.

2.2.1.9 Current sense

The current sense input senses the current regulator MOSFET source. It causes the gate drive output to increase or decrease to force the current sense voltage to match the current reference. The reference for power factor mode is 1.291 volts average, 2.03 volt peak. The reference for dim mode is 1.5 volts. In triac dim mode the reference is DC. During the dimmer off-time the EMI capacitor C8 will charge. R29, 54.9 Kohm prevents excess voltage on the CS pin when the triac fires and D11 directs C8 energy back to VCC

2.2.1.10 Compensation

A 4.7 uF capacitor is used to keep the loop response below the rectified AC frequency. This allows the average current sense reference voltage to be 1.291 volts while allowing the 120 HZ frequency through to achieve high power factor. If the loop response was above the rectified AC frequency the TPS92410 would try to respond to the changing voltage on the multiplier pin causing poor power factor.

2.2.1.11 Vin/Vcc

The TPS92410 directly connects to the rectified AC to provide a bias voltage to run its circuitry, Vcc.

2.2.1.12 EMI control

A capacitor, C8, across the discrete current regulator MOSFET gate to source, Q3, along with the TPS92411 slew control allows the reference design to pass QP conducted EMI with 4.1dB of margin with only a 0.1 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 and the power rating of the damper resistors network would need to double. R16, 100 ohm keeps the phase margin of the TPS92410 loop acceptable.

3 Electrical Performance Specifications

Table 1: TPS92410/TPS92411 reference design Electrical Performance Specifications

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNITS
Input Characteristics					
Voltage range	Normal operation	207	230/240	264	V
Voltage range	Maximum range	200		265	V
Maximum input current	At 230 Vrms input		0.090		A rms
Input power			20	22.5	watts
Output Characteristics					
Output voltage, stack 1 (top)	Nominal		168		V
Output voltage, stack 2	Nominal		78		V
Output voltage, stack 3	Nominal		36		V
Output voltage, stack 4 (bottom)	Nominal		18		V

4 Schematic

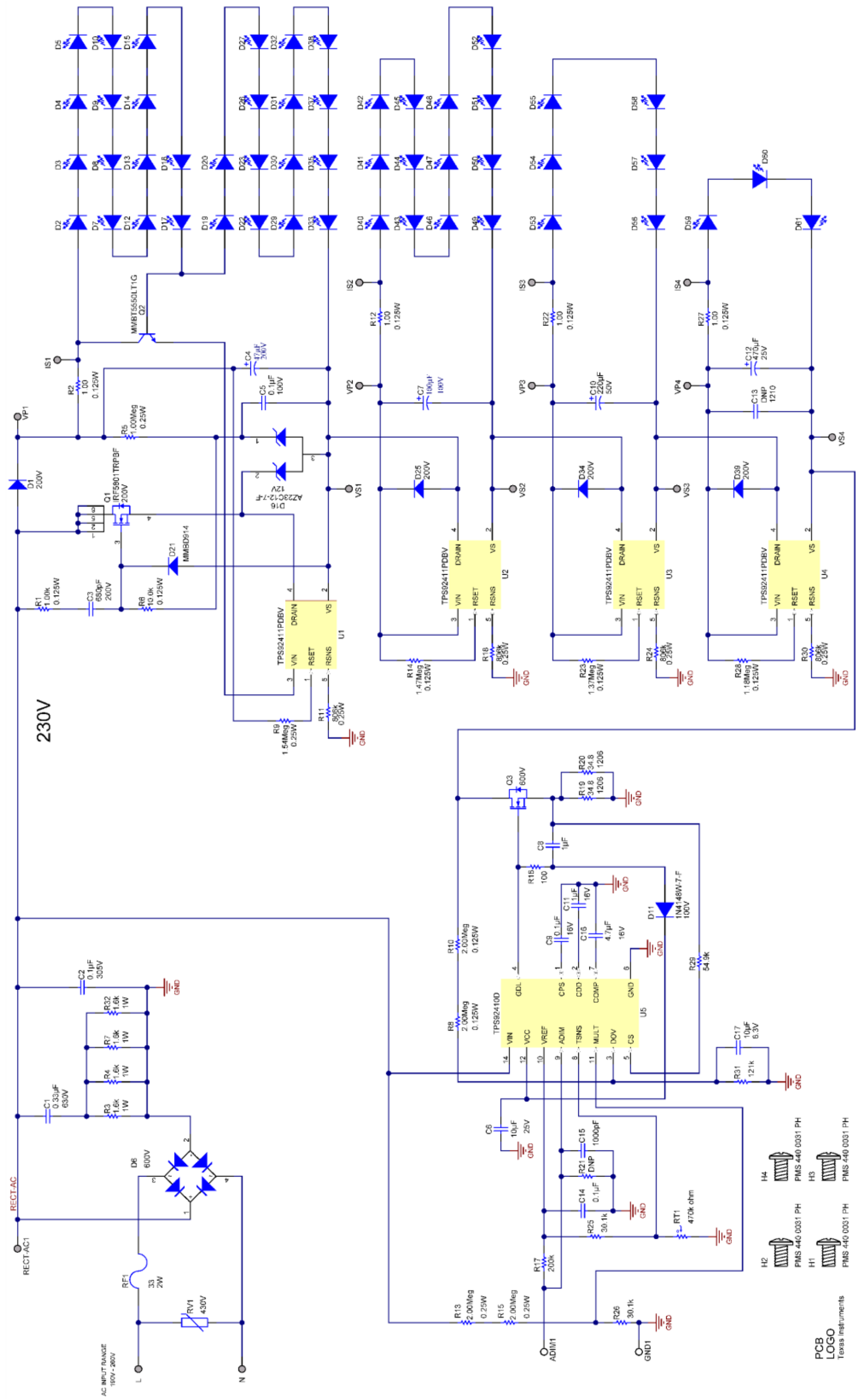

Figure 1: TPS92411 discrete linear Schematic

5 Performance Data and Typical Characteristic Curves

Figures 2 through 30 present typical performance curves for TPS92411 discrete design.

5.1 Efficiency

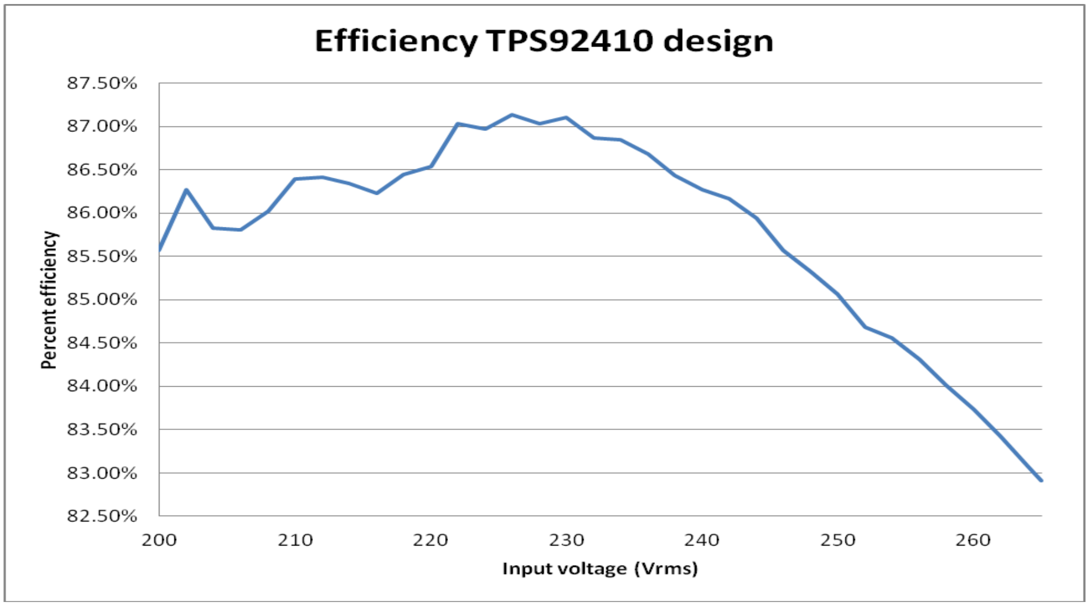

Figure 2: Efficiency

5.2 Line Regulation

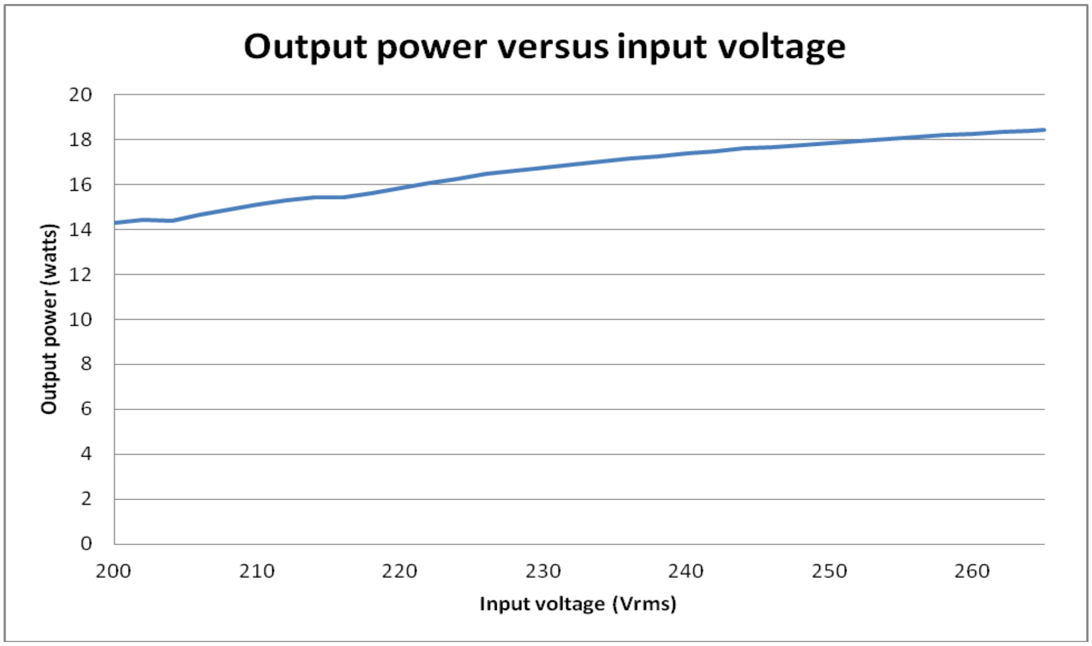

Figure 3: Line Regulation

5.3 Power Factor

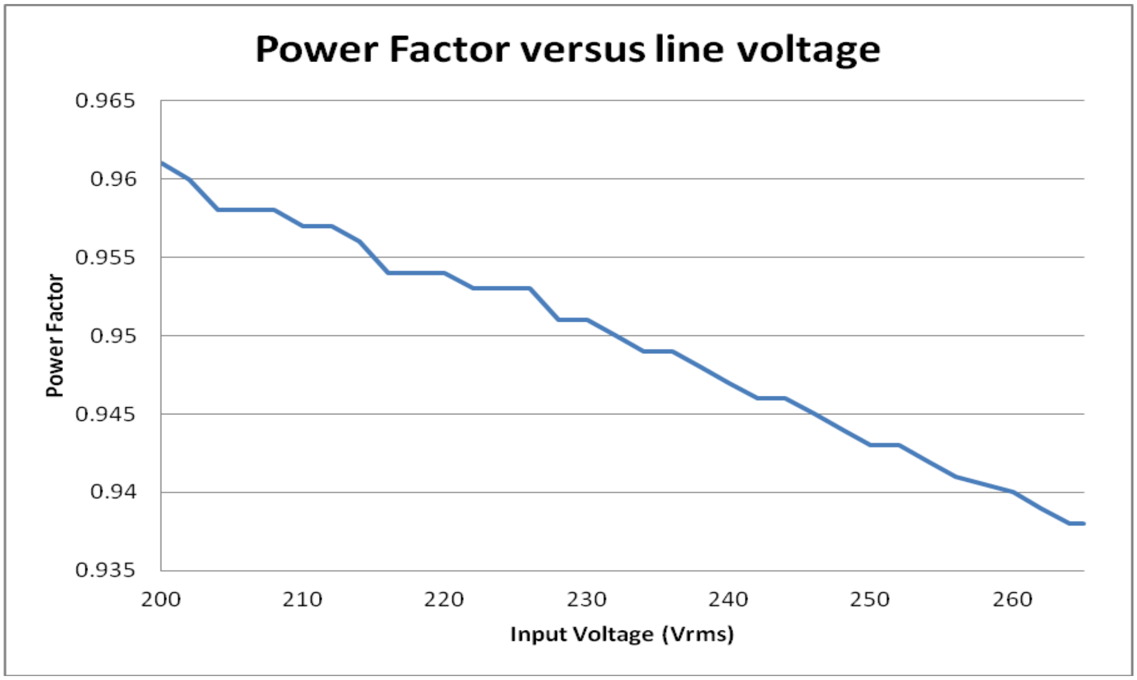

Figure 4: Power factor correction at 60 Hz, PF at 230 VAC@50Hz is 0.961

5.4 Total Harmonic Distortion

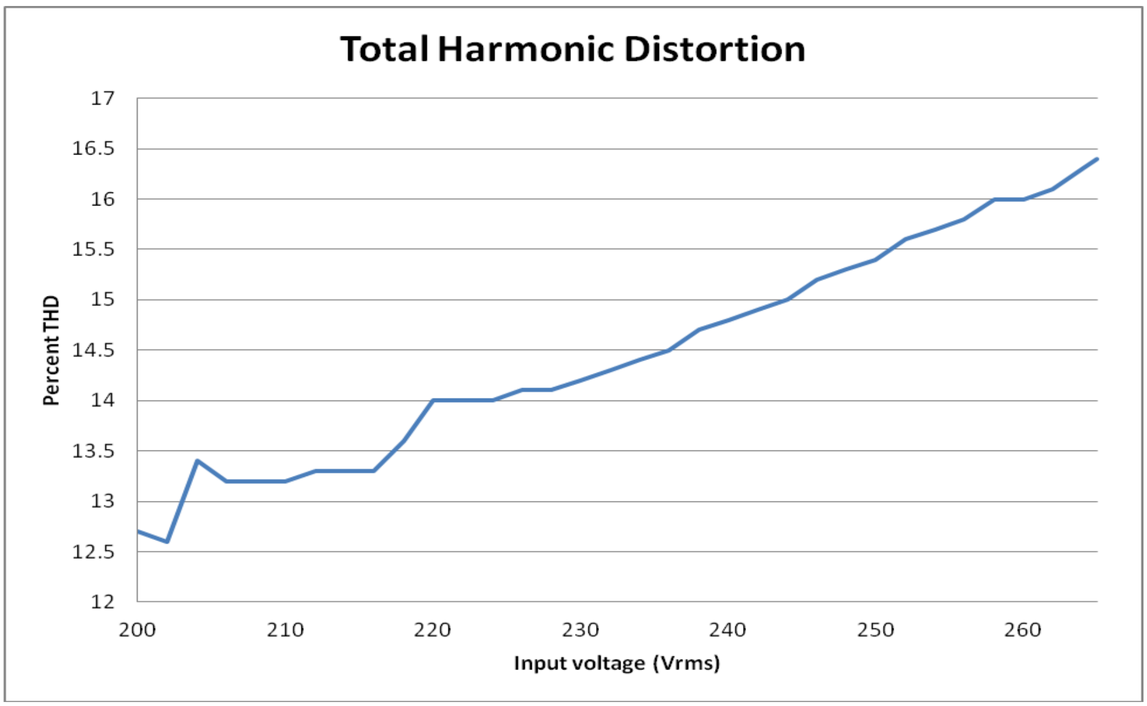

Figure 5: Total Harmonic Distortion at 60Hz, THD at 230 VAC@50Hz is 0.12

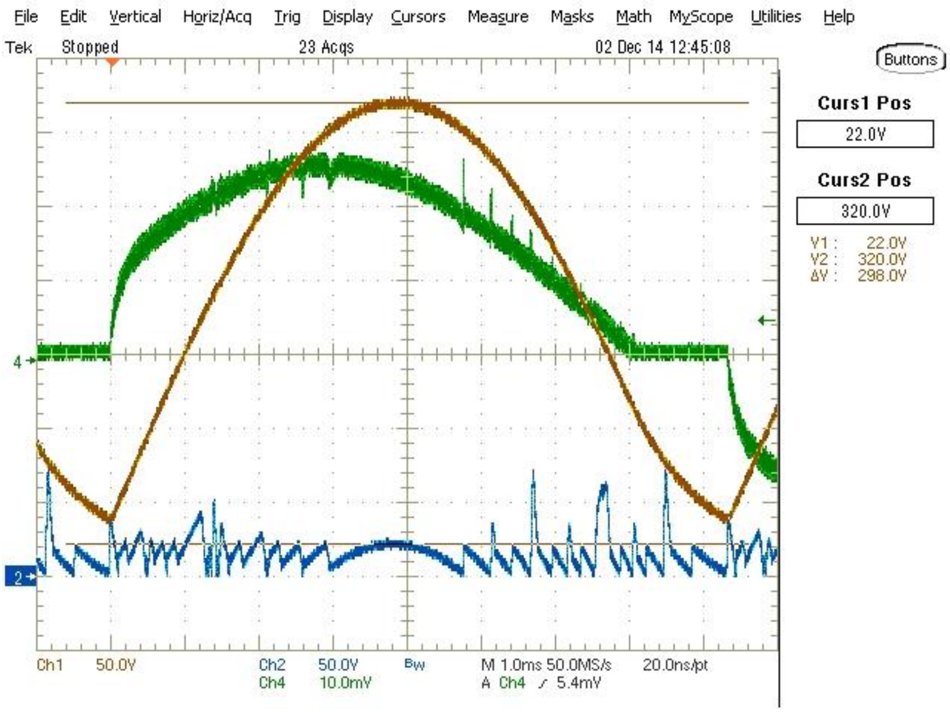

Figure 6: Current regulator drain waveform (Blue), rectified AC (brown), and input current (green). The area between the rectified AC and the drain waveform is the voltage applied to the LED sections in their various TPS92411 switch states.

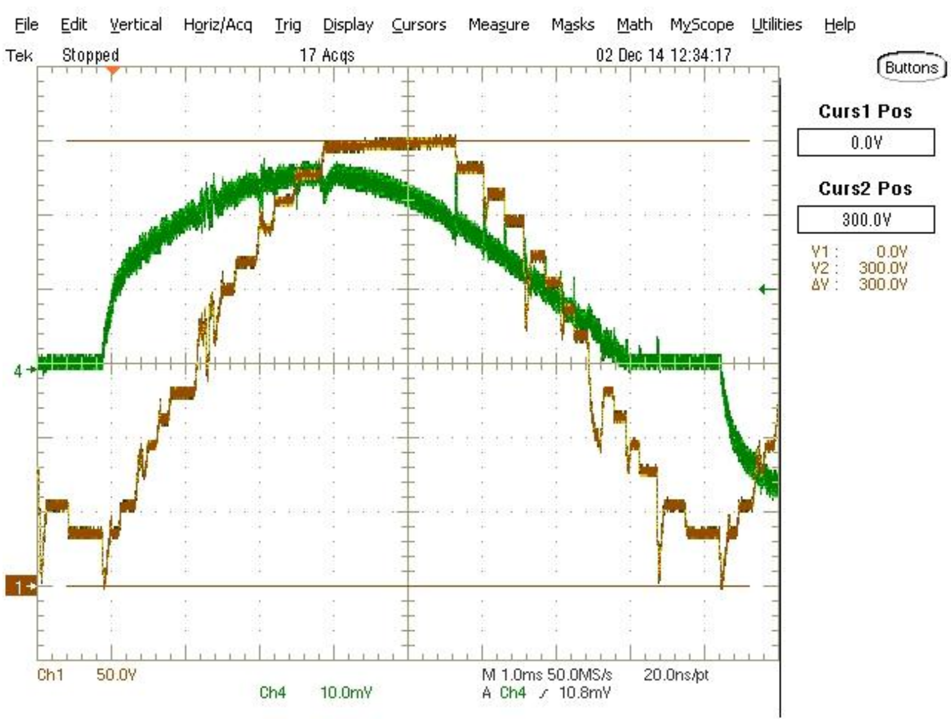

Figure 7: Applied voltage to LED sections during various TPS92411 states (Figure 6 brown waveform minus Figure 6 blue waveform)

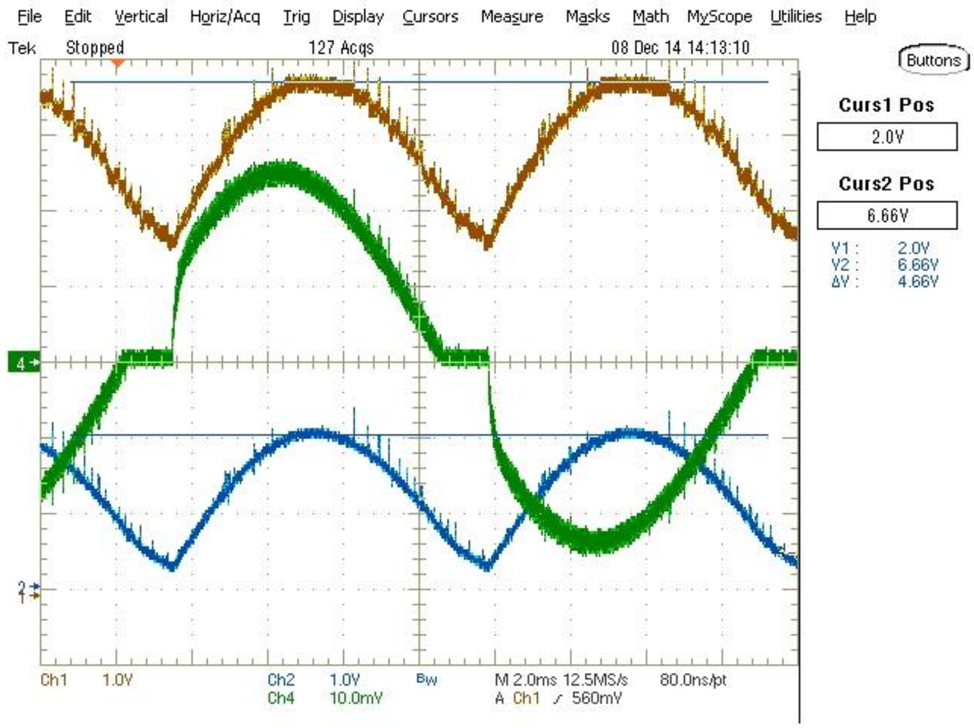

Figure 8: Current regulator MOSFET gate voltage (brown), and source voltage/current sense (blue)

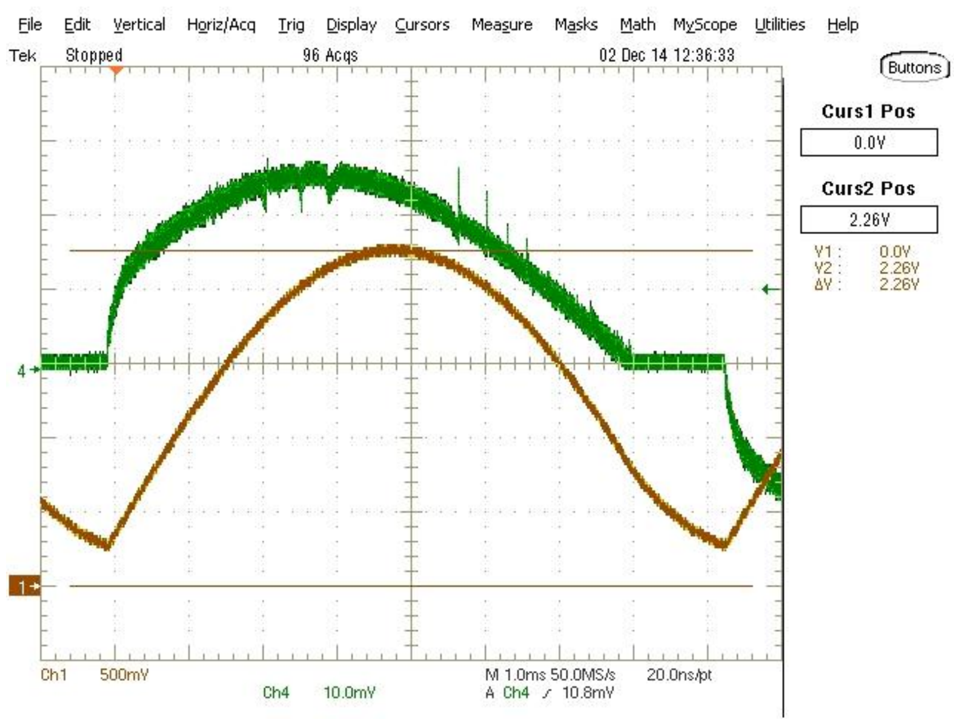

Figure 9: TPS92410 multiplier input (brown)

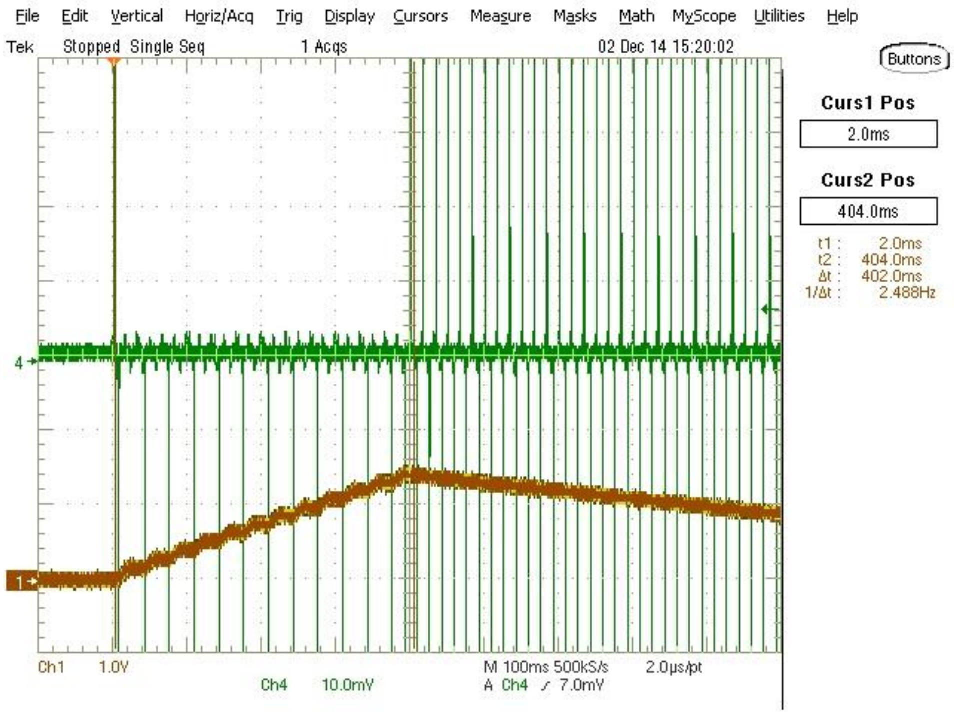

Figure 10: CDD voltage with forward phase dimmer, CDD ramping up until switch to DC mode (dimmer at mid-point)

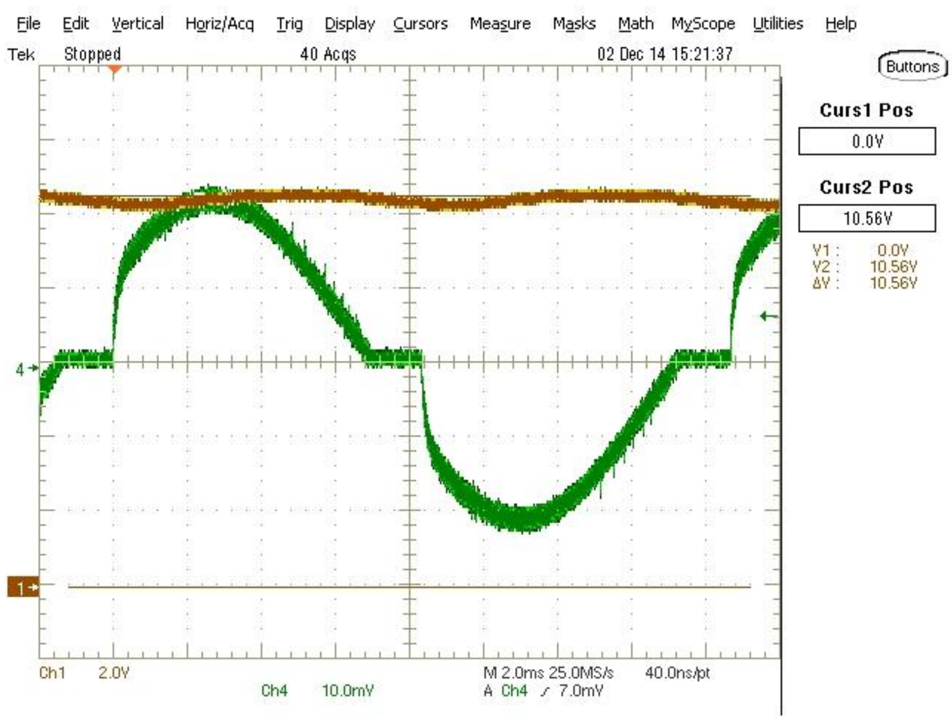

Figure 11: TPS92410 VCC, internally generated from Rectified AC

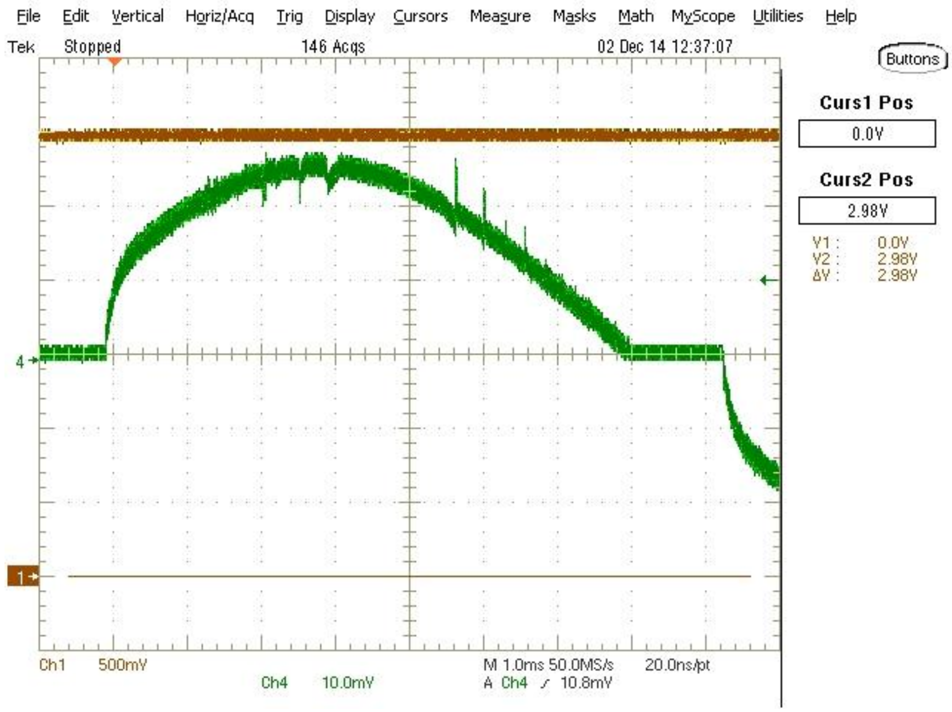

Figure 12: TPS92410 Vref, external 3.0 volt reference used for TSN, ADIM

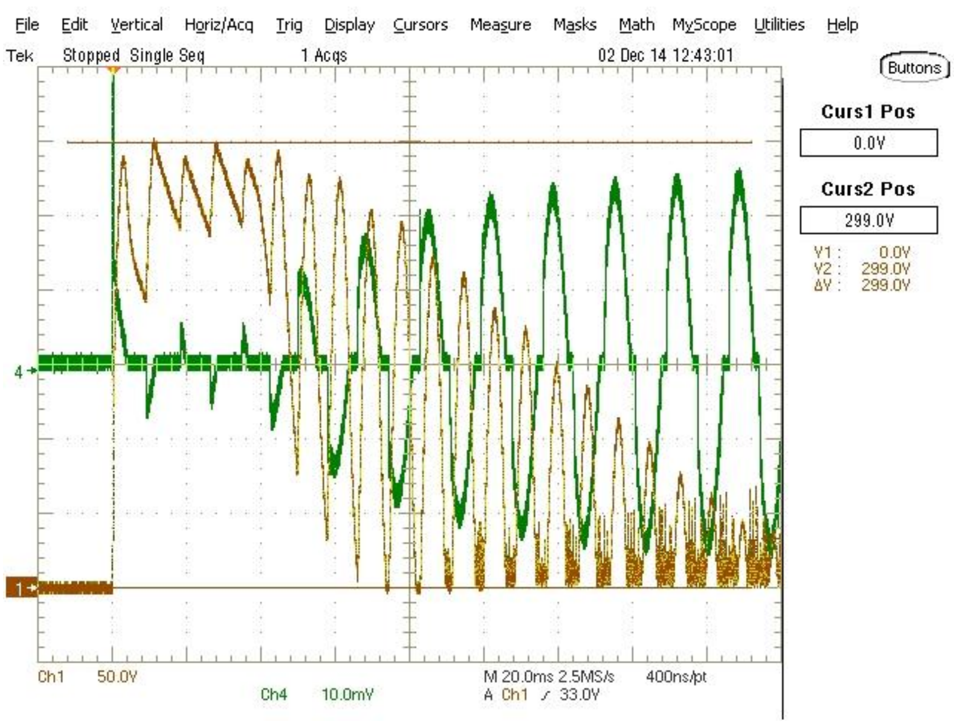

Figure 13: Drain voltage during turn-on (brown), input current (green)

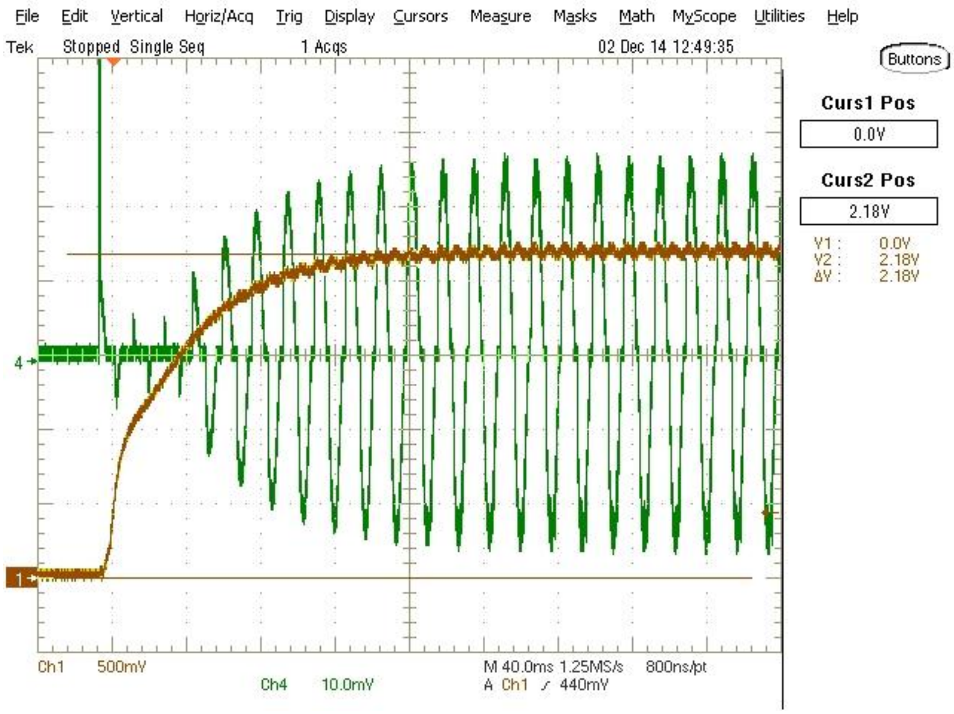

Figure 14: TPS92410 Compensation pin during start-up (brown), input current (green)

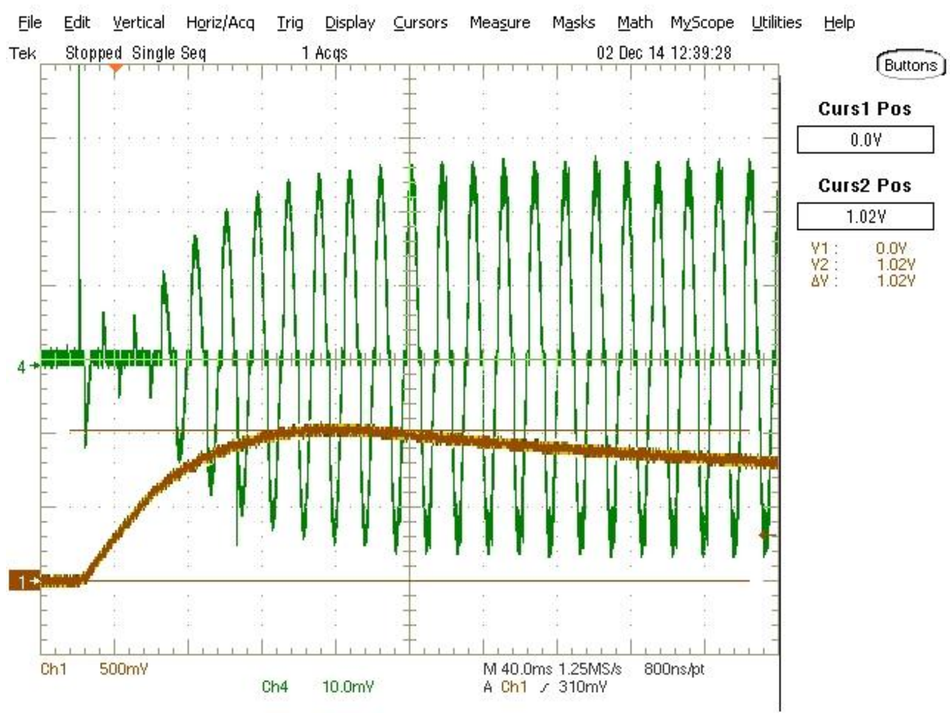

Figure 15: TPS92410 DOV pin during start-up at 230 VAC

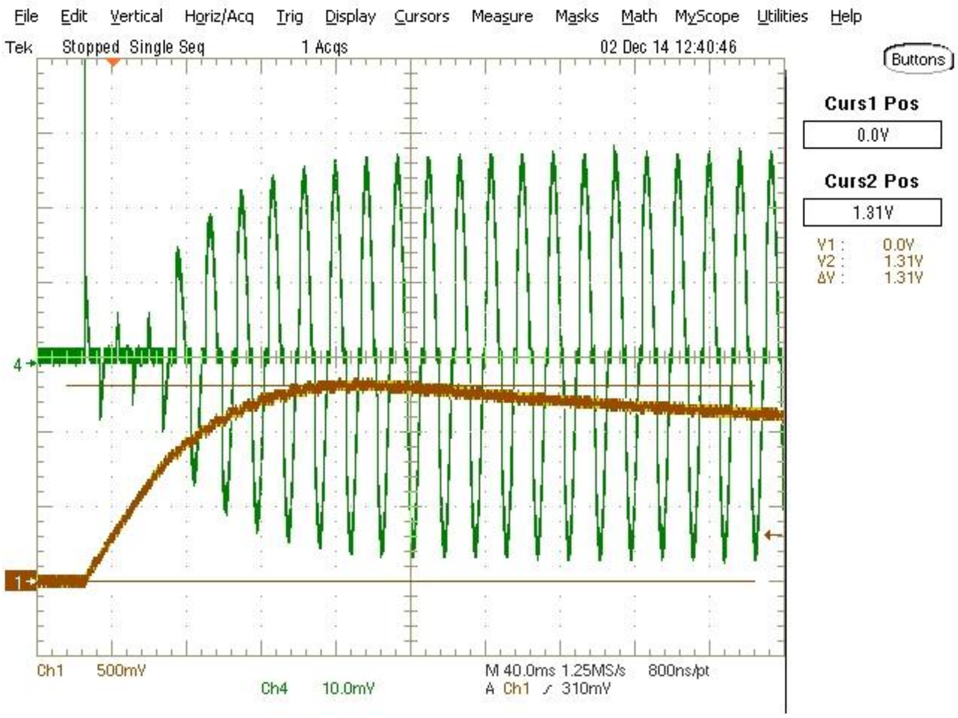

Figure 16: TPS92410 DOV pin during start-up at 265 VAC, DOV trips at 1.5 volts

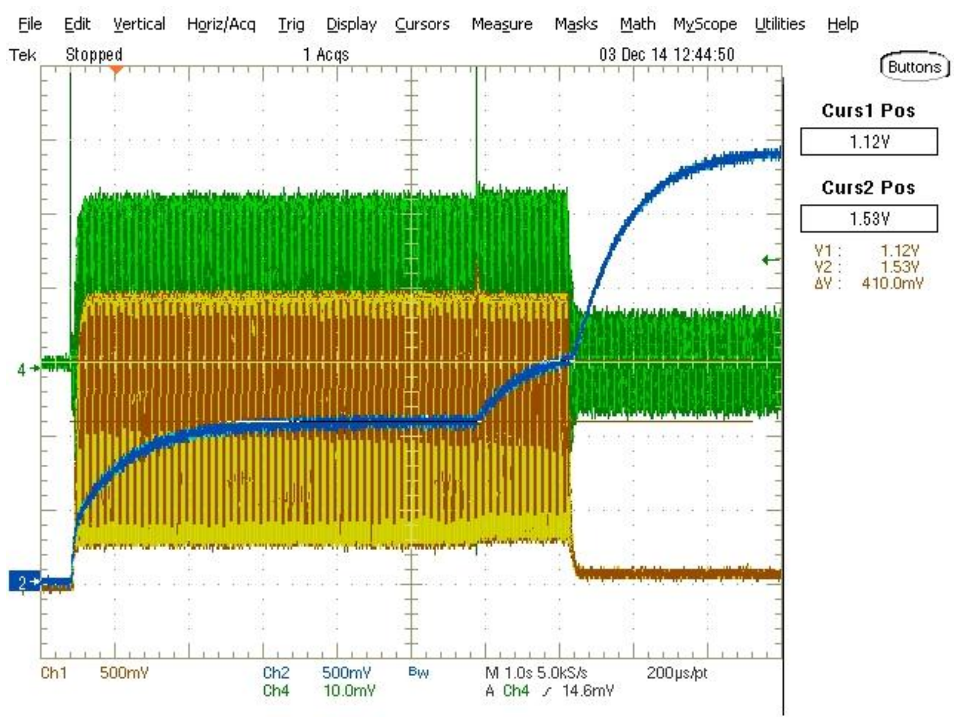

Figure 17: TPS92410 DOV pin with stack three shorted, change input voltage from 230 VAC to 265 VAC. DOV (blue) trips at 1.5 volts, current regulator goes into low power mode

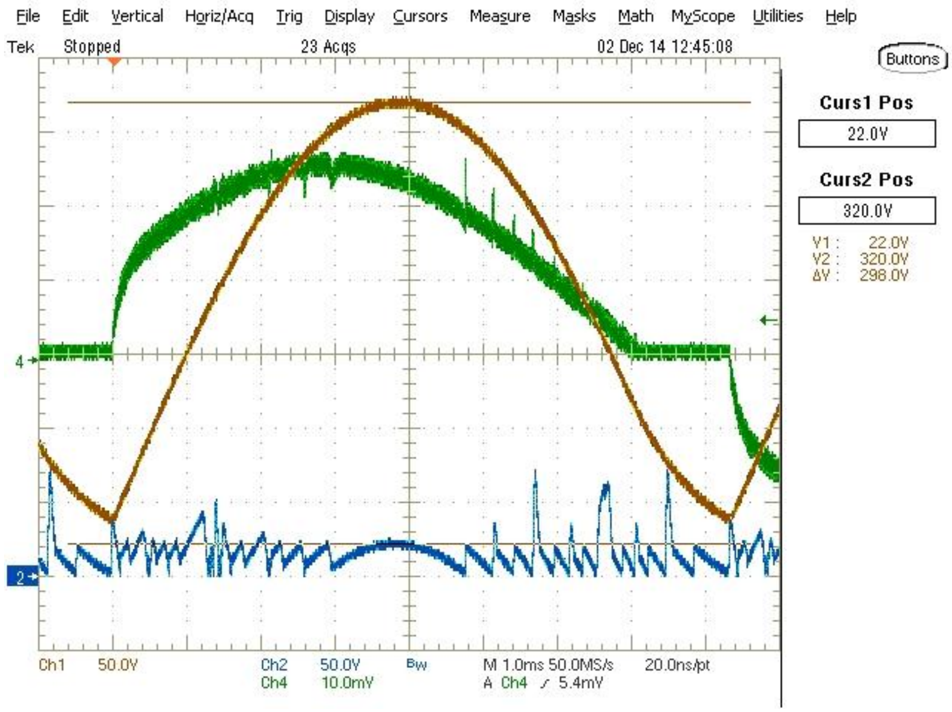

Figure 18: Rectified AC (brown)

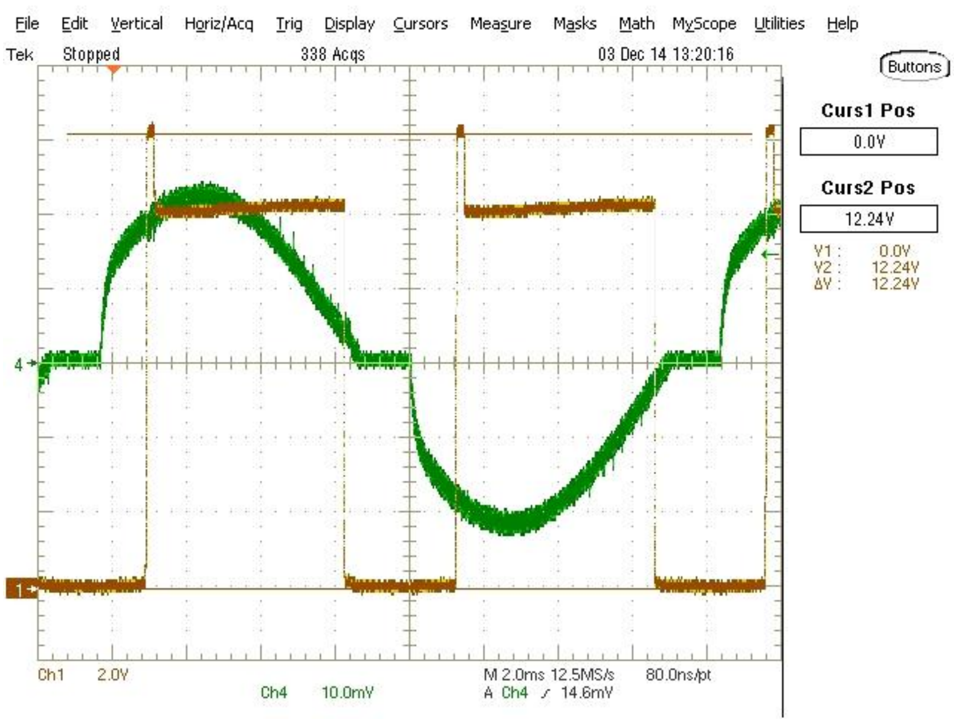

Figure 19: Upper TPS92411 drain waveform, cascode drive, allows slew control and no inversion

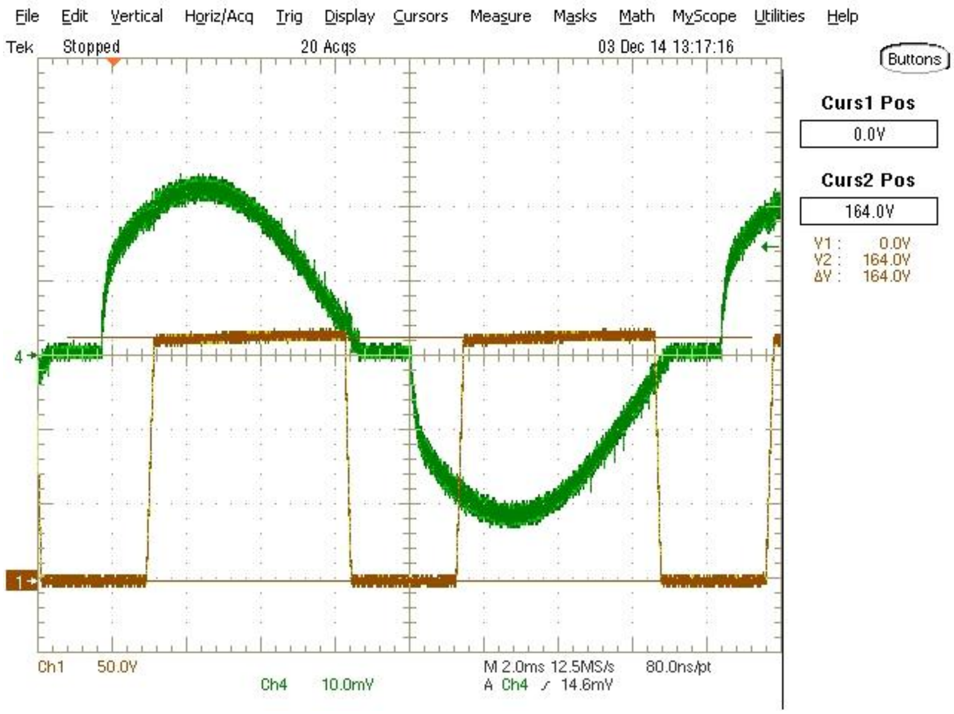

Figure 20: Drain of cascode MOSFET showing slew control, turn-on faster than turn-off. 1st stack, 168 volt, 1xxx in count sequence

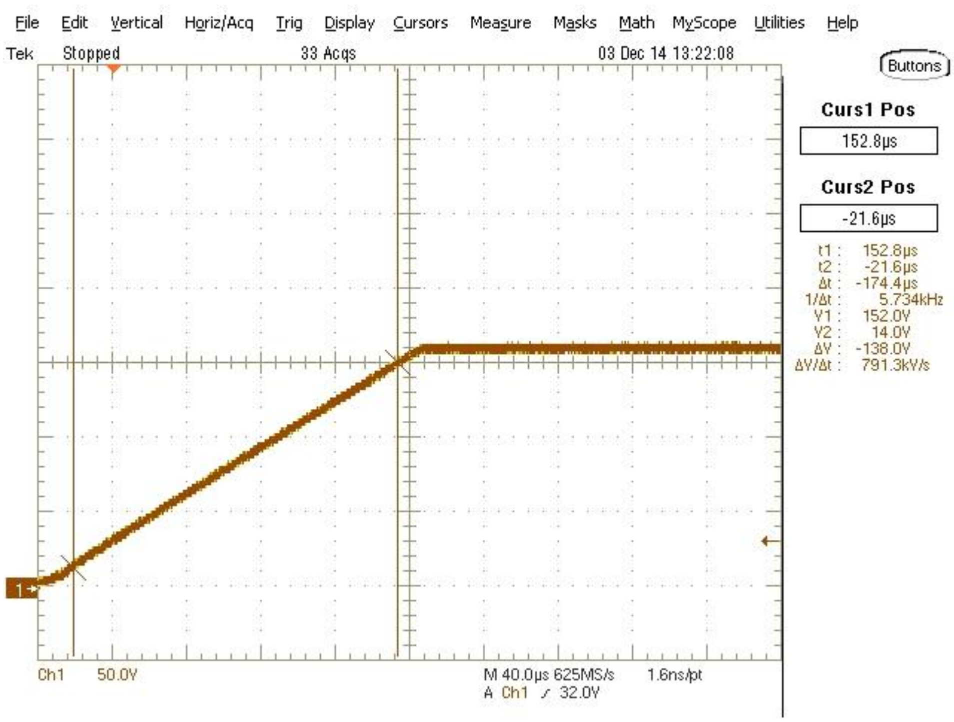

Figure 21: Drain of cascode MOSFET, open slew, 0.791V/uS

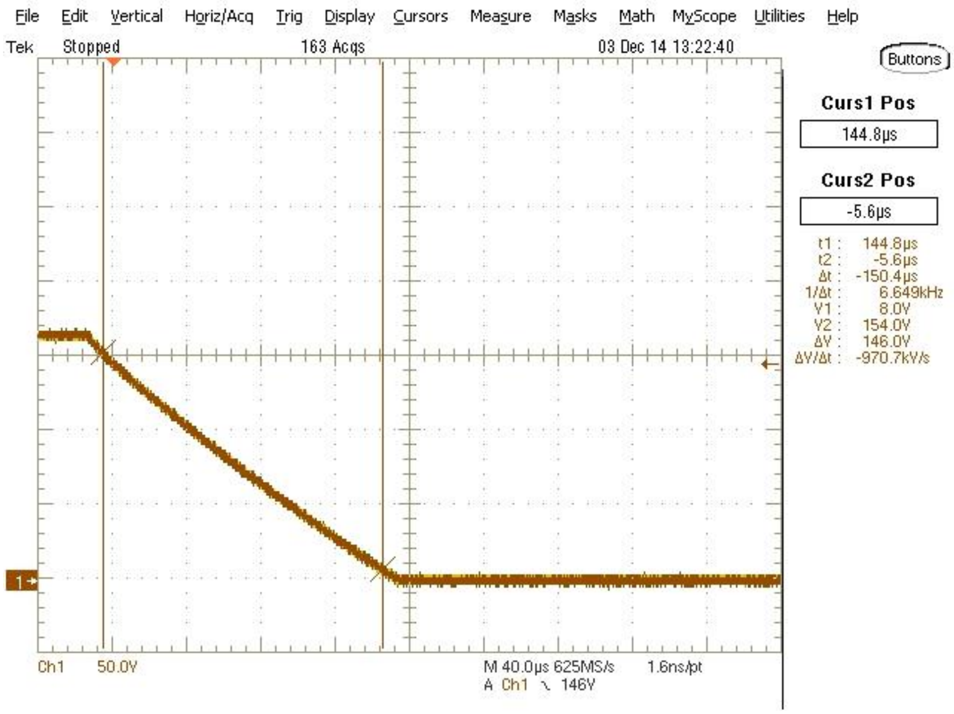

Figure 22: Drain of cascode MOSFET, close slew, -0.971V/uS

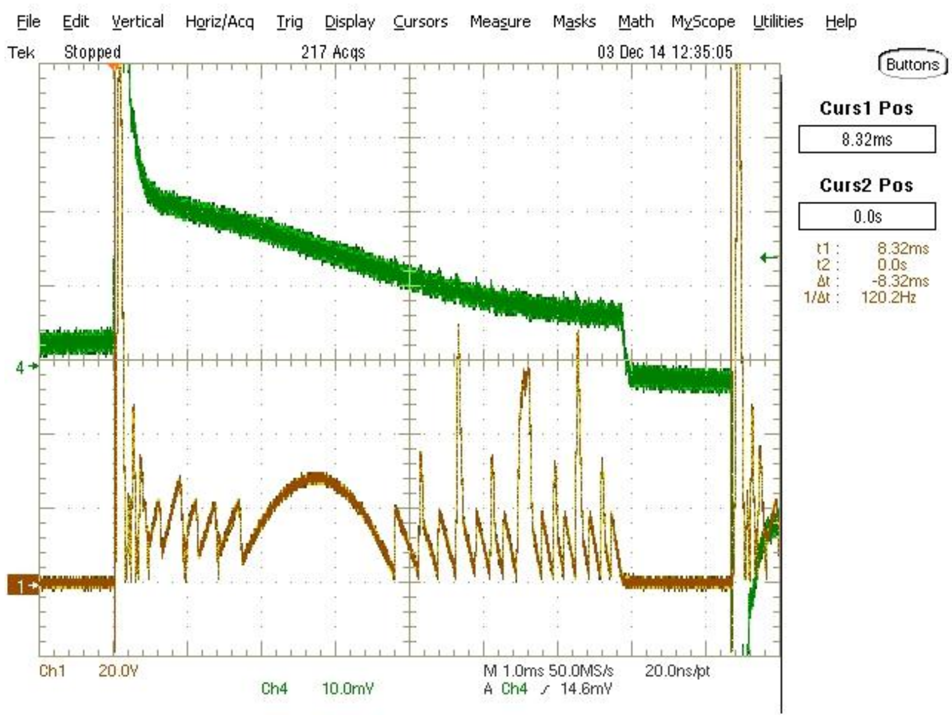

Figure 23: MOSFET drain waveform (brown) and input current with triac dimmer at maximum. In DC reference mode (dim detect triggered), input current slope caused by EMI capacitor and damper capacitor.

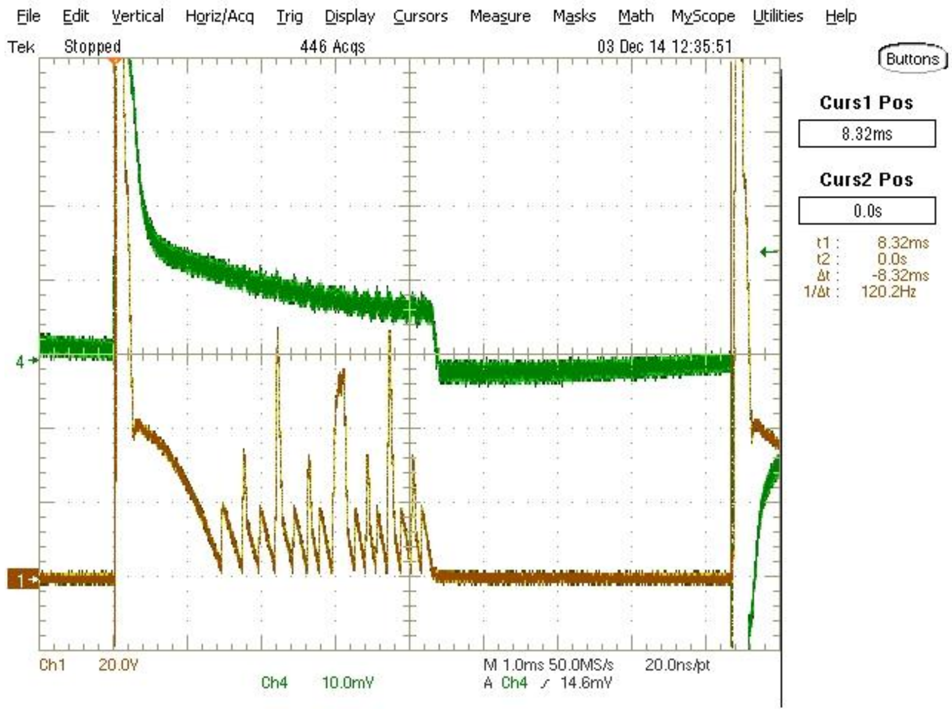

Figure 24: MOSFET drain waveform (brown) and input current with triac dimmer at ½ setting

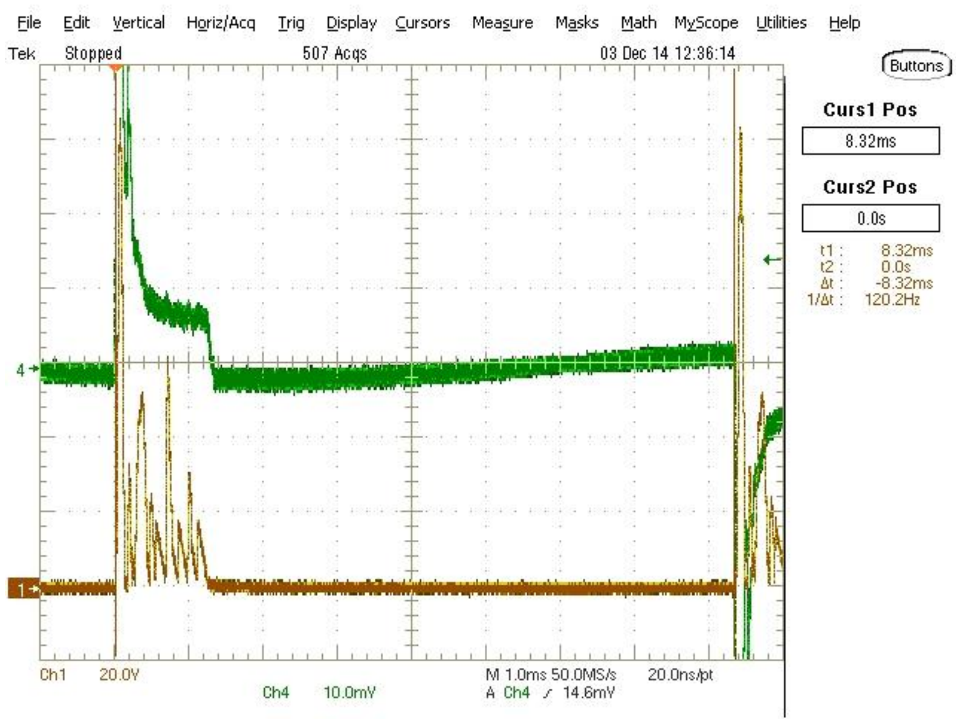

Figure 25: MOSFET drain waveform (brown) and input current with triac dimmer at minimum setting

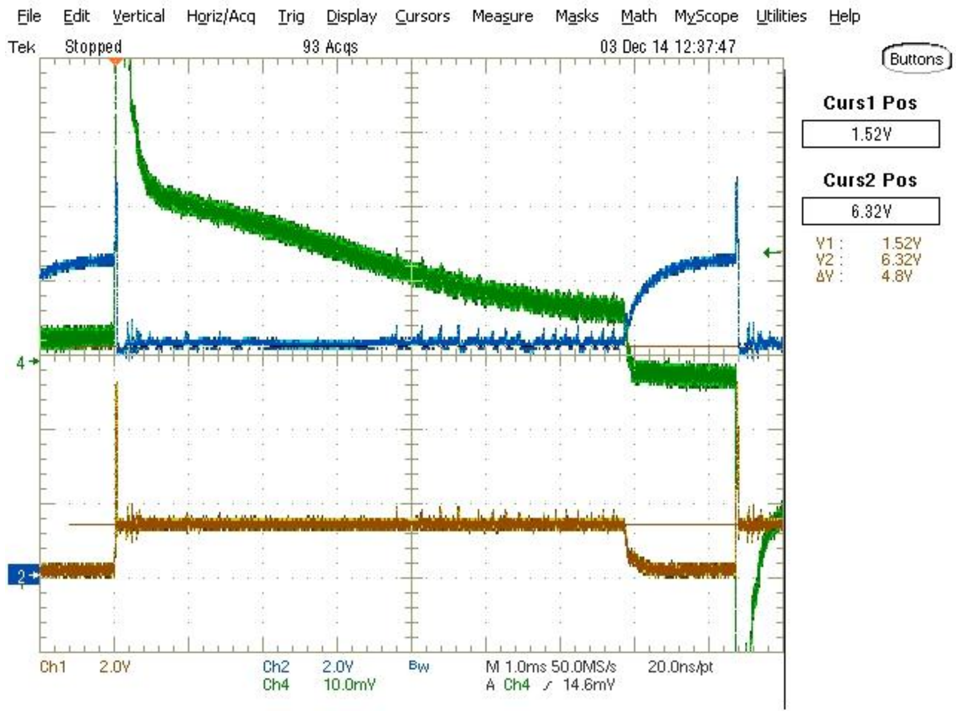

Figure 26: Q3 MOSFET gate (blue) and source (brown) in dim detect mode, current sense is flat 1.5 volts. Gate charging when dimmer is off, D11 to discharge VGS capacitor when triac fires

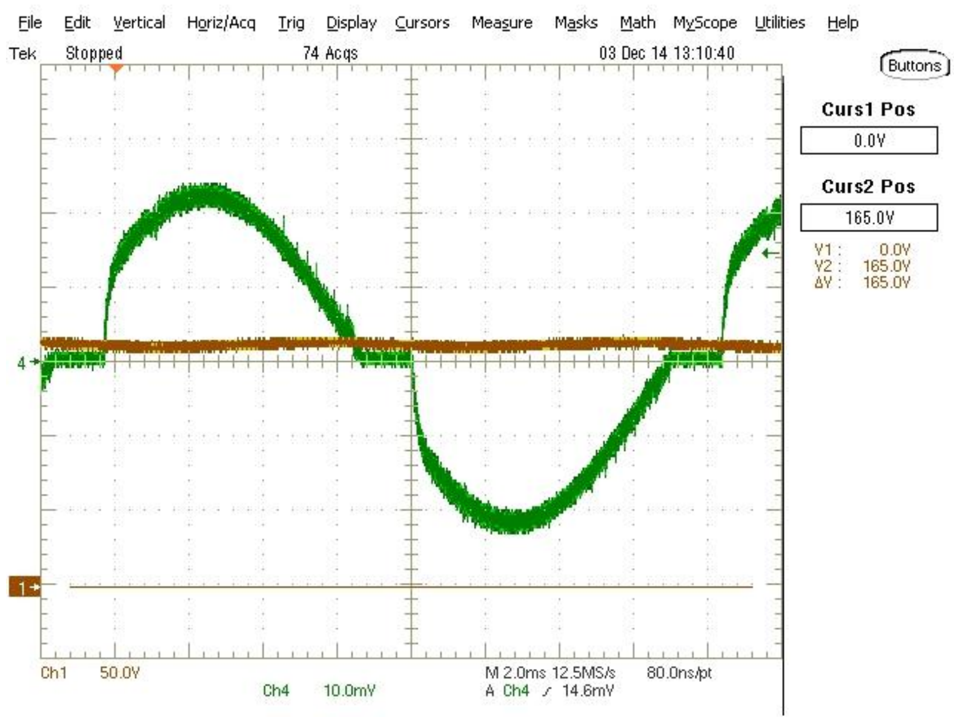

Figure 27: Stack one voltage, approximately 165 VDC

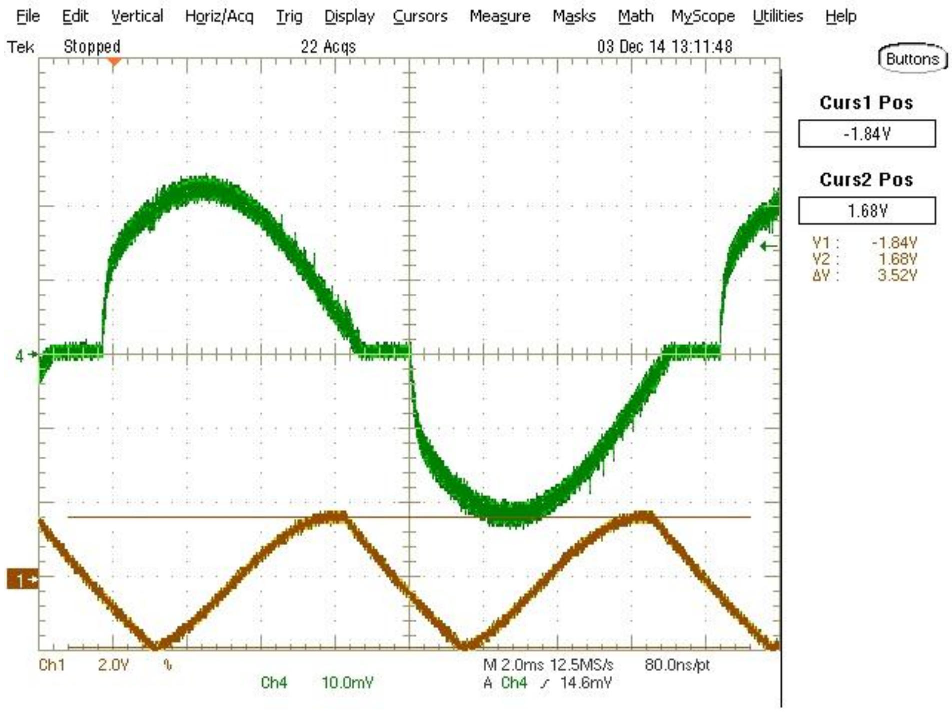

Figure 28: Voltage ripple stack one

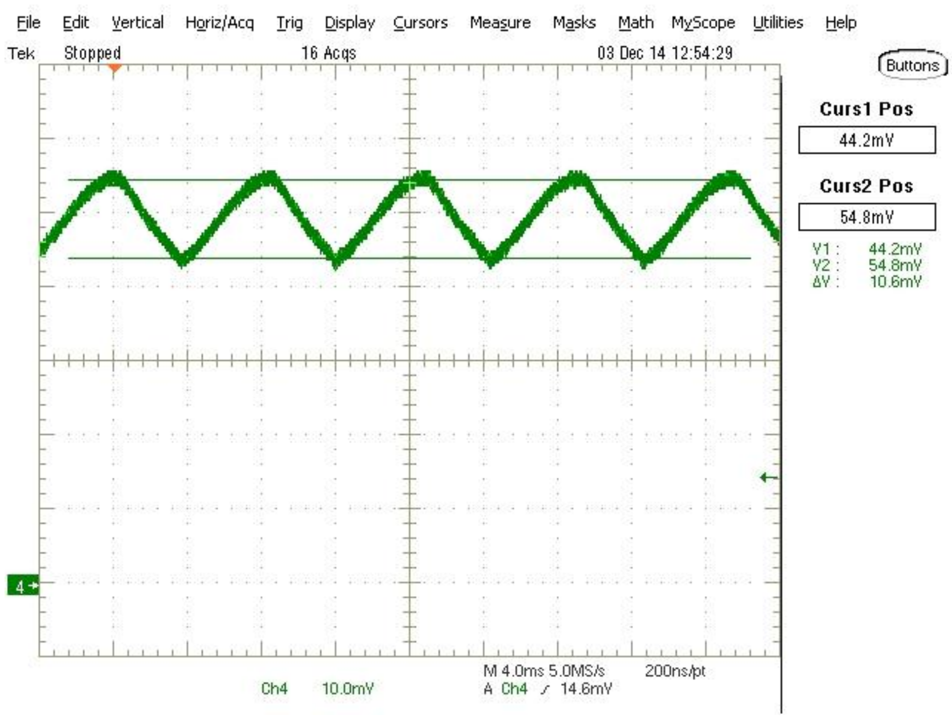

Figure 29: current ripple stack one, approximately 21% peak to peak ripple

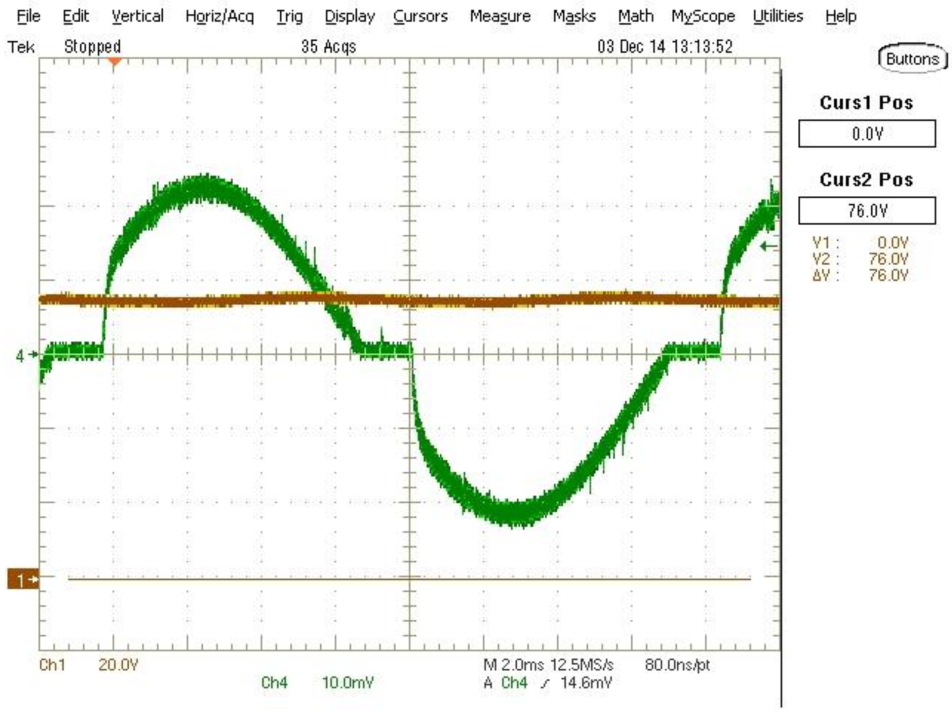

Figure 30: Stack two voltage, approximately 76.0 volts

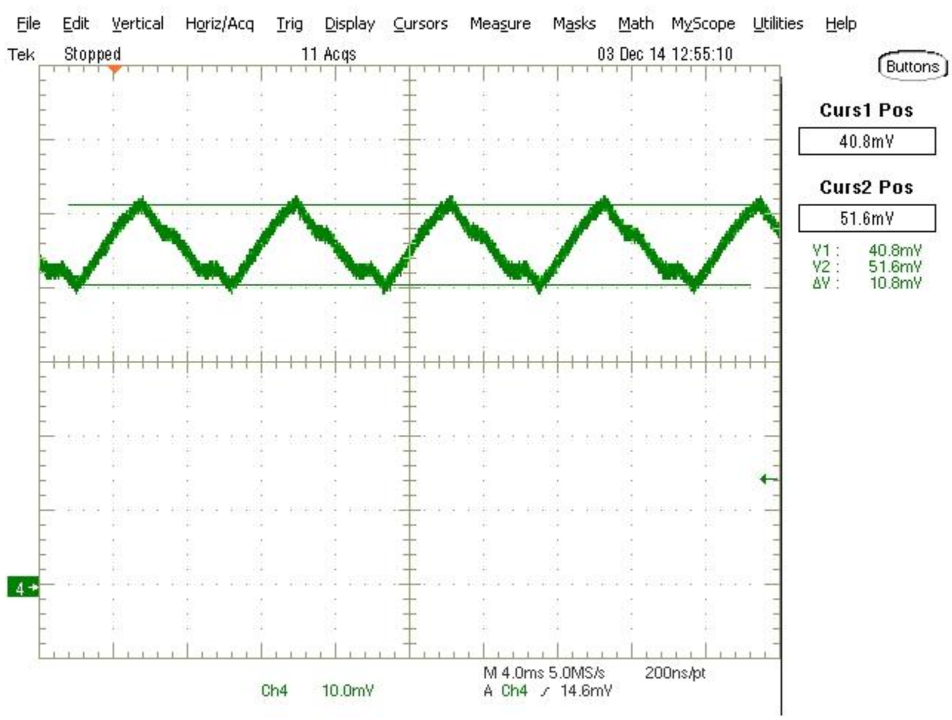

Figure 31: current ripple stack two, approximately 23% peak to peak ripple

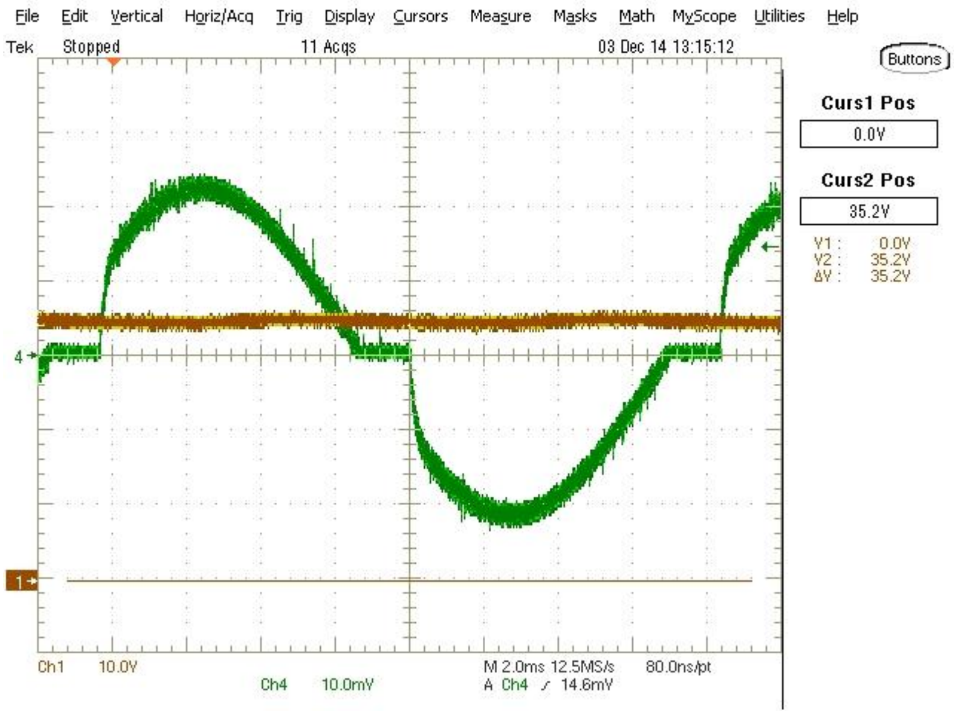

Figure 32: Stack three voltage, approximately 35.2 volts

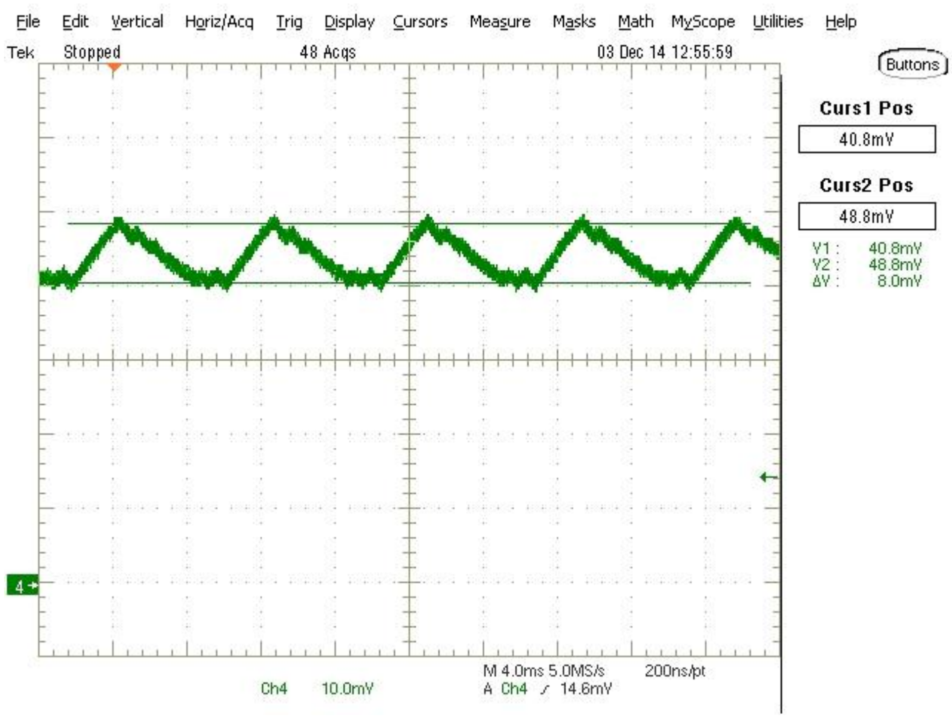

Figure 33: current ripple stack three, approximately 18% ripple

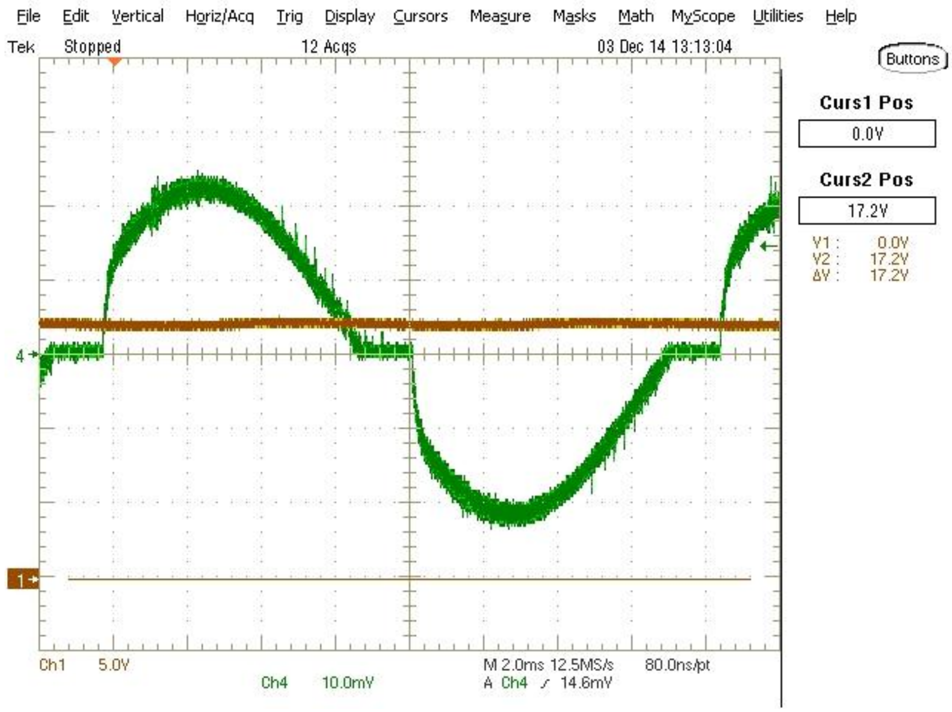

Figure 34: Stack four voltage, approximately 17.2 volts

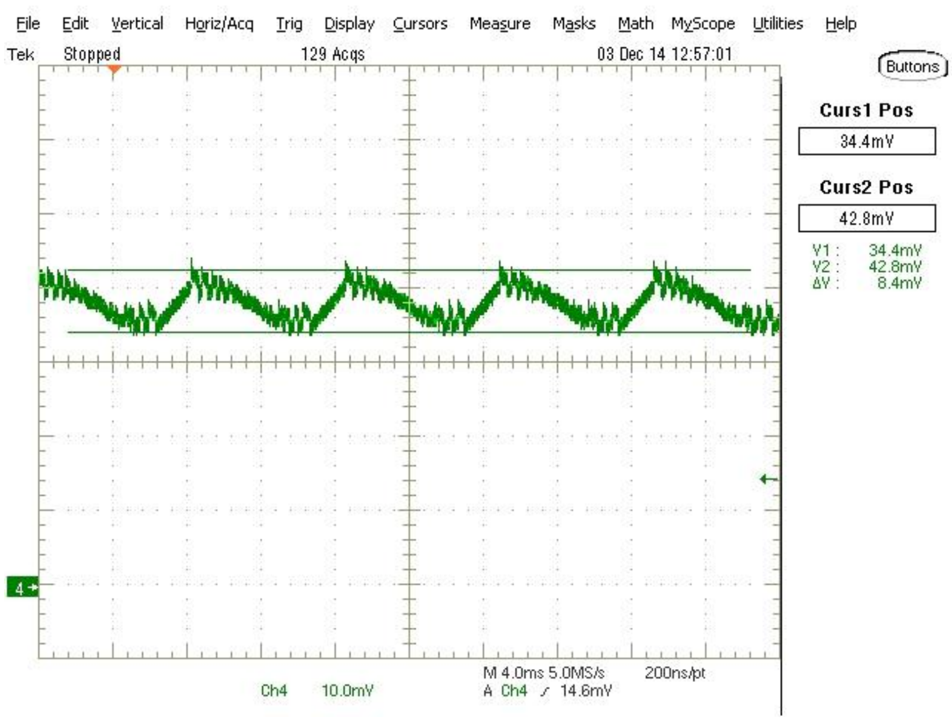

Figure 35: current ripple stack three, approximately 22% ripple

5.3 *EMI Performance*

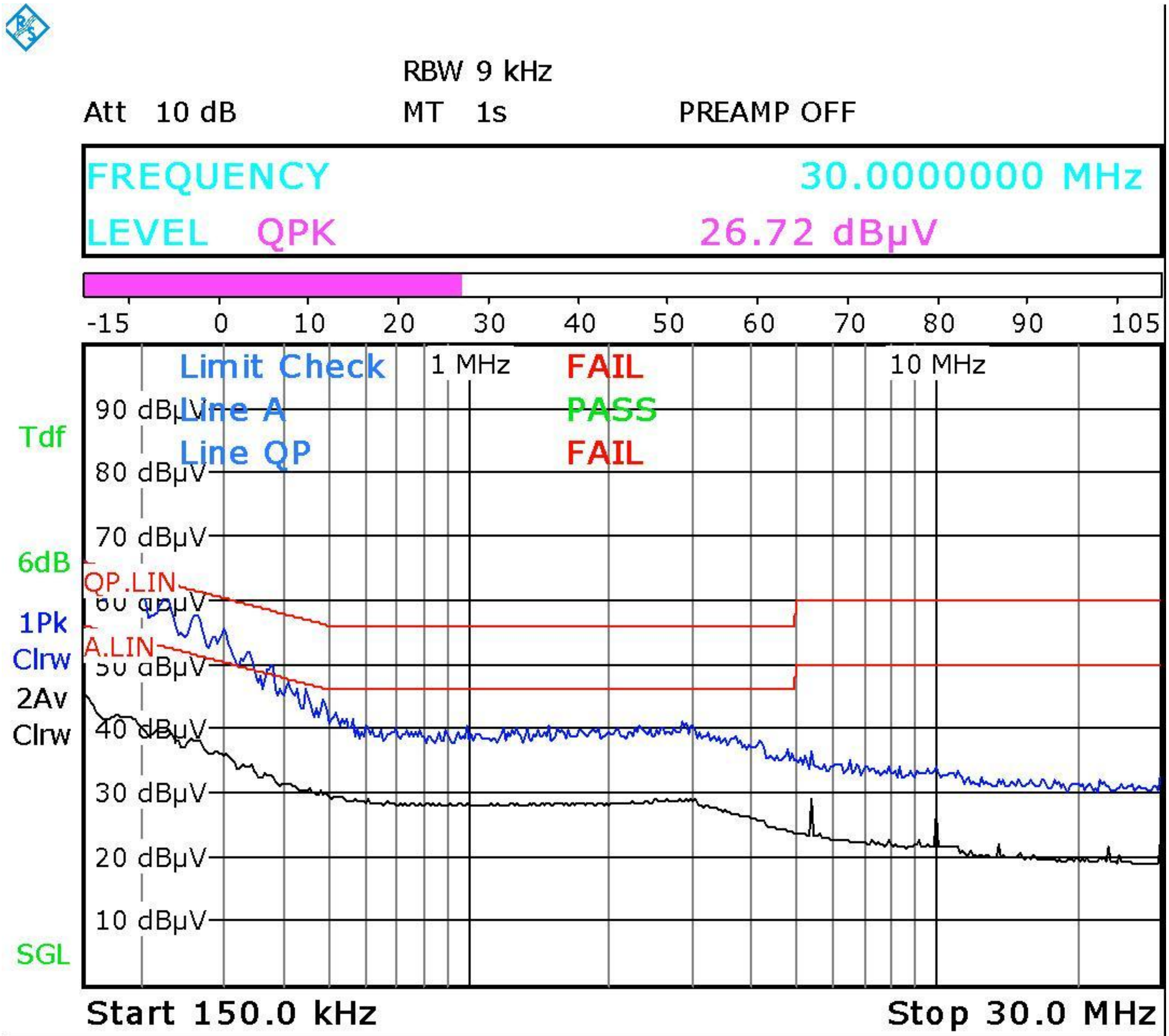

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Figure 36: Conducted EMI scan peak and average, Quasi-peak measures -4.1 dB for both line and neutral at 150 KHz

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

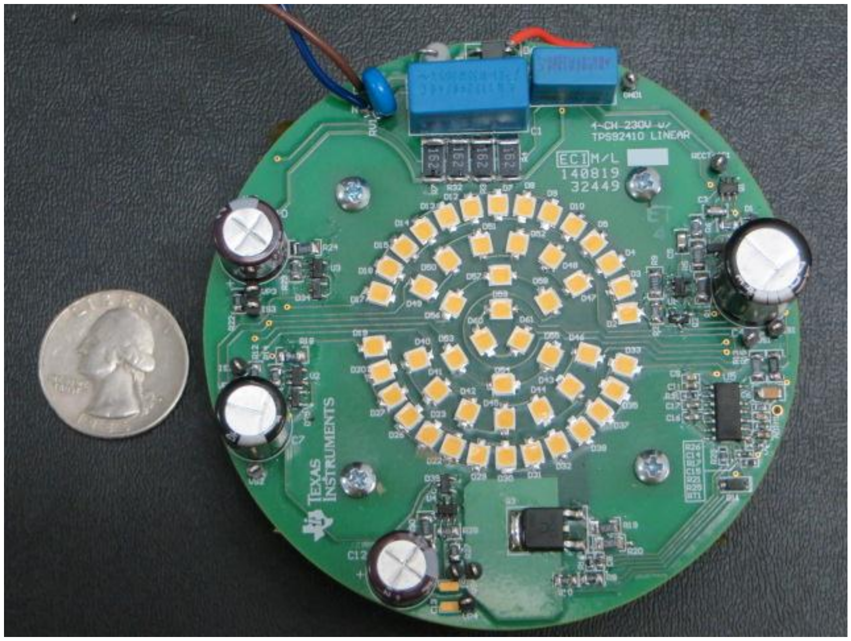

Figure 37: Four layer board with heat spreading planes, mounted to ½-brick heatsink for testing

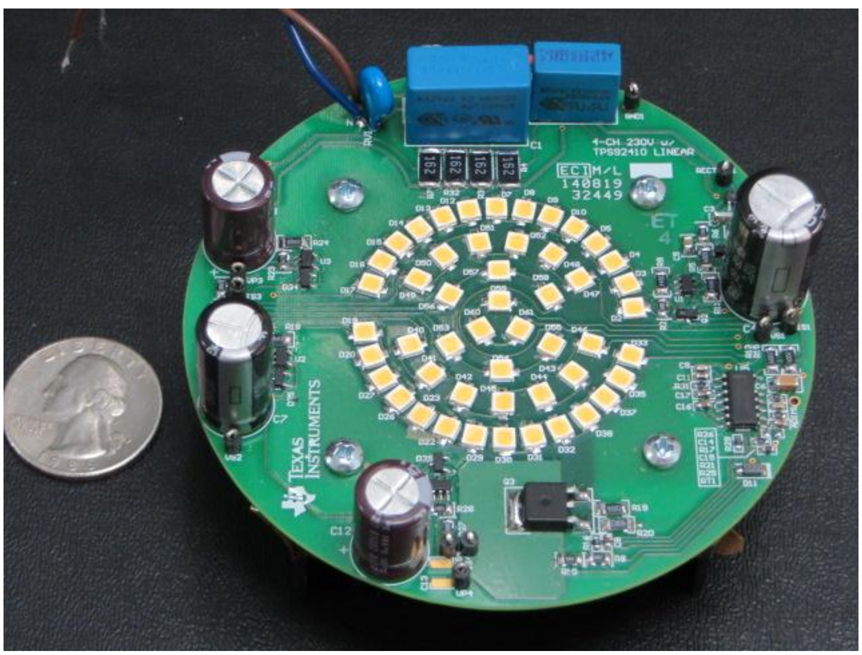

Figure 38: FR4 SMT section including four TPS92411s and TPS92410

6 TPS92411 Reference Design PCB layout

The following figures (Figure 39 through Figure 40) show the design of the TPS92410/TPS92411 printed circuit board.

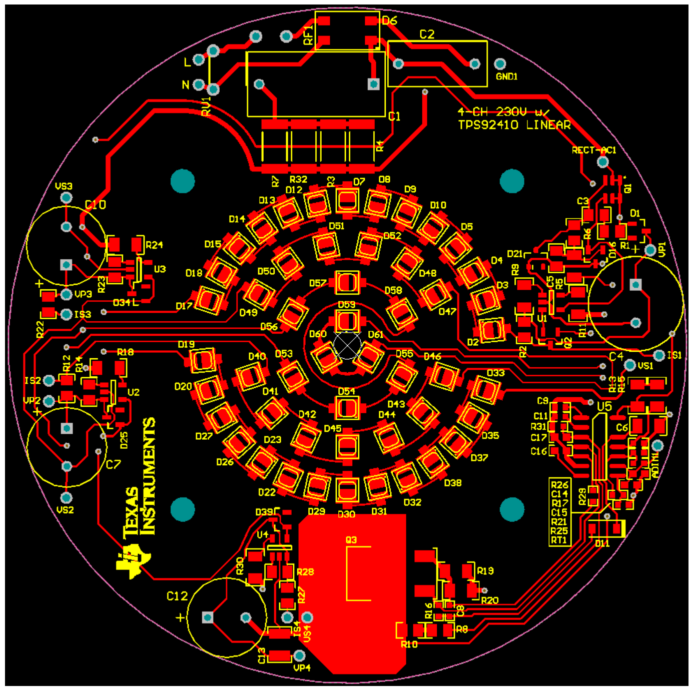

Figure 39: Top Layer and Top Overlay (Top view)

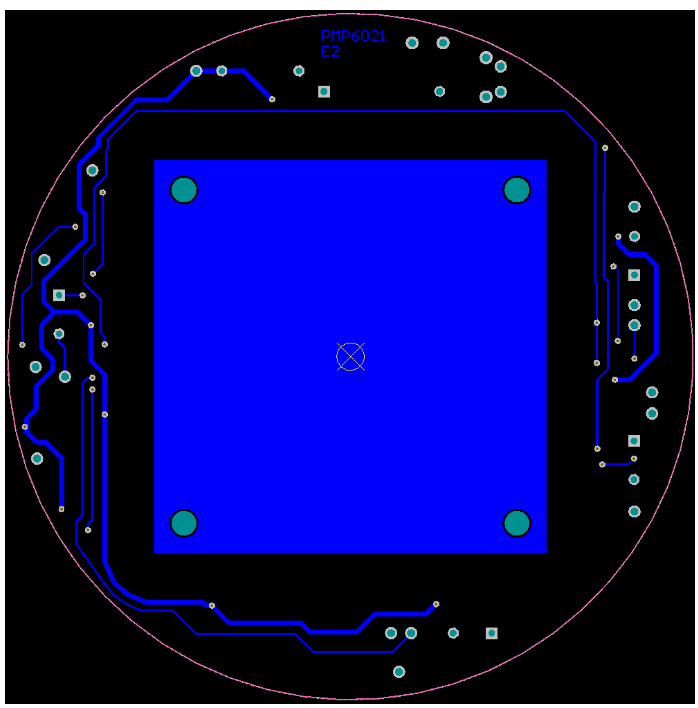

Figure 40: Bottom Layer and Bottom Overlay (Bottom view)

7 Bill of Materials

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

REFERENCE DESIGNATOR	QTY	VALUE	DESCRIPTION	SIZE	MFR	PART NUMBER
ADIM1, GND1	2	SMT	Test Point, Miniature, SMT		Keystone	5015
C1	1	0.33uF	CAP, Film, 0.33 µF, 630 V, +/-20%, TH	B32922_14.5mm	EPCOS Inc	B32922C3334M
C2	1	0.1uF	CAP, Film, 0.1 µF, 305 V, +/-20%, TH	13x6x12mm	EPCOS Inc	B32921C3104M
C3	1	680pF	CAP, CERM, 680 pF, 200 V, +/- 10%, X7R, 0805	0805	Yageo America	CC0805KRX7RABB681
C4	1	47uF	CAP, AL, 47uF, 200V, +/-20%, 0.380955 ohm, TH	12.5x20	Panasonic	EEUED2D470
C5	1	0.1uF	CAP, CERM, 0.1uF, 100V, +/-10%, X7R, 0805	0805	Samsung	CL21B104KCFSFNE
C6	1	10uF	CAP, CERM, 10uF, 25V, +/-10%, X7R, 1206	1206	MuRata	GRM31CR71E106KA12L
C7	1	100uF	CAP, AL, 100uF, 100V, +/-20%, TH	10x20mm	Panasonic	ECA-2AHG101
C8, C11	2	1uF	CAP, CERM, 1uF, 16V, +/-10%, X7R, 0603	0603	TDK	C1608X7R1C105K
C9, C14	2	0.1uF	CAP, CERM, 0.1uF, 16V, +/-5%, X7R, 0603	0603	Kemet	C0603C104J4RACTU
C10	1	220µF	CAP, Alum, 220uF, 50V, +/-20%, Radial	Radial, Can	Nichicon	UPW1H221MPD
C12	1	470µF	CAP, Alum, 470uF, 25V, +/-20%, Radial	Radial, Can	Nichicon	UPW1E471MPD
C15	1	1000pF	CAP, CERM, 1000pF, 50V, +/-10%, X7R, 0603	0603	MuRata	GRM188R71H102KA01D
C16	1	4.7uF	CAP, CERM, 4.7uF, 16V, +/-10%, X5R, 0603	0603	MuRata	GRM188R61C475KAAJ
C17	1	10µF	CAP, CERM, 10uF, 6.3V, X5R, 20%, 0603	0603 (1608 Metric)	Taiyo Yuden	JMK107ABJ106MAHT
D1, D25, D34, D39	4	200V	Diode, Switching, 200V, 0.2A, SOT-23	SOT-23	Diodes Inc.	BAS21-7-F

D2, D3, D4, D5, D7, D8, D9, D10, D12, D13, D14, D15, D17, D18, D19, D20, D22, D23, D26, D27, D29, D30, D31, D32, D33, D35, D37, D38, D40, D41, D42, D43, D44, D45, D46, D47, D48, D49, D50, D51, D52, D53, D54, D55, D56, D57, D58, D59, D60, D61	50		LED SMD NEUTRAL WHITE 4000K	2-SMD, No Lead	Seoul Semiconductor Inc	STW8C2SA-J19K24-EA
D6	1		Diode, Switching-Bridge, 600V, 0.8A, MiniDIP	MiniDIP	Diodes Inc.	HD06-T
D11	1	100V	Diode, Ultrafast, 100V, 0.15A, SOD-123	SOD-123	Diodes Inc.	1N4148W-7-F
D16	1	12V	Diode, Zener, 12V, 300mW, SOT-23	SOT-23	Diodes Inc.	AZ23C12-7-F
D21	1	100V	Diode, P-N, 100 V, 0.2 A, SOT-23	SOT-23	Fairchild Semiconductor	MMBD914
H1, H2, H3, H4	4		MACHINE SCREW PAN PHILLIPS 4-40		B&F Fastener Supply	PMS 440 0031 PH
Q1	1	200V	MOSFET, N-CH, 200V, 0.6A, TSOP-6	TSOP-6	International Rectifier	IRF5801TRPBF
Q2	1	0.25V	Transistor, NPN, 140V, 0.6A, SOT-23	SOT-23	ON Semiconductor	MMBT5550LT1G
Q3	1	600V	MOSFET, N-CH, 600V, 2A, DPAK	DPAK	AOS	AOD2N60
R1	1	1.00k	RES, 1.00k ohm, 1%, 0.125W, 0805	0805	Vishay-Dale	CRCW08051K00FKEA
R2, R12, R22, R27	4	1.00	RES, 1.00 ohm, 1%, 0.125W, 0805	0805	Stackpole Electronics Inc	RMCF0805FT1R00
R3, R4, R7, R32	4	1.6k	RES, 1.6k ohm, 5%, 1W, 2512	2512	Vishay-Dale	CRCW25121K60JNEG
R5	1	1.00Meg	RES, 1.00Meg ohm, 1%, 0.25W, 1206	1206	Vishay-Dale	CRCW12061M00FKEA

R6	1	10.0k	RES, 10.0k ohm, 1%, 0.125W, 0805	0805	Vishay-Dale	CRCW080510K0FKEA
R8, R10	2	2.00Meg	RES, 2.00Meg ohm, 1%, 0.125W, 0805	0805	Vishay-Dale	CRCW08052M00FKEA
R9	1	1.54Meg	RES, 1.54Meg ohm, 1%, 0.25W, 1206	1206	Vishay-Dale	CRCW12061M54FKEA
R11, R18, R24, R30	4	806k	RES, 806k ohm, 1%, 0.25W, 1206	1206	Vishay-Dale	CRCW1206806KFKEA
R13, R15	2	2.00Meg	RES, 2.00Meg ohm, 1%, 0.25W, 1206	1206	Vishay-Dale	CRCW12062M00FKEA
R14	1	1.47Meg	RES, 1.47Meg ohm, 1%, 0.125W, 0805	0805	Vishay-Dale	CRCW08051M47FKEA
R16	1	100	RES, 100 ohm, 1%, 0.1W, 0603	0603	Vishay-Dale	CRCW0603100RFKEA
R17	1	200k	RES, 200k ohm, 1%, 0.1W, 0603	0603	Vishay-Dale	CRCW0603200KFKEA
R19, R20	2	34.8	RES, 34.8, 1%, 0.25 W, 1206	1206	Vishay-Dale	CRCW120634R8FKEA
R23	1	1.37Meg	RES, 1.37Meg ohm, 1%, 0.125W, 0805	0805	Vishay-Dale	CRCW08051M37FKEA
R25, R26	2	30.1k	RES, 30.1k ohm, 1%, 0.1W, 0603	0603	Vishay-Dale	CRCW060330K1FKEA
R28	1	1.18Meg	RES, 1.18Meg ohm, 1%, 0.125W, 0805	0805	Vishay-Dale	CRCW08051M18FKEA
R29	1	54.9k	RES, 54.9k ohm, 1%, 0.1W, 0603	0603	Vishay-Dale	CRCW060354K9FKEA
R31	1	121k	RES, 121k ohm, 1%, 0.1W, 0603	0603	Vishay-Dale	CRCW0603121KFKEA
RF1	1	33	RES 33 OHM 2W 10% AXIAL	Axial	TT Electronics/Welwyn	EMC2-33RKI
RT1	1	470k ohm	Thermistor NTC, 470k ohm, 5%, 0603	0603	MuRata	NCP18WM474J03RB
RV1	1	430V	Metal Oxide Varistor, TH	9.00 mm Diameter	Bourns	MOV-07D431K
U1, U2, U3, U4	4		Switch Controlled Direct Drive Switch for Offline LED Drivers, DBV0005A	DBV0005A	Texas Instruments	TPS92411PDBV
U5	1		Switch Controlled Direct Drive Linear Controller for Offline LED Drivers, D0013A	D0013A	Texas Instruments	TPS92410D

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