National Semiconductor

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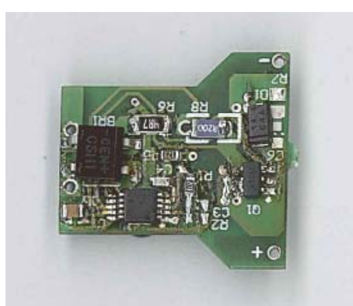
Part number **LM3409HV**

Project Title **4.87W LED MR16 for electronic transformer**

Project Number **REF261**

Title		**4.87W LED MR16 for electronic transformer**
Norm	Lighting	
Norm	EMI	
Description	Input	$11.5V_{AC.rms}$
	Output	3 LEDs @ 350mA
	Power	3.5W LEDs
	Efficiency	Up to 67%
Date		[2011-05-09]
Revision		[2.3]



Contents

1 Introduction

This new LED MR16 will replace the standard halogen by driving 3 high power LEDs.

This following report describes the design and shows practical test results of this LED-based MR16 designed to drive 3 LEDs in series from an AC input voltage of 11.5VAC rms generated by 50Hz magnetic transformers or Electronic transformers.

Halogen MR16 bulbs do not flicker because the light emitted depends on the heat of the wire in the bulb. The heat changes more slowly compared with the change in current (50Hz) from the mains. The light emitted by LEDs changes instantly with the current. Therefore special measures need to be taken to avoid flickering.
The solution is to create a system that has a power factor close to 1 to get the same behavior as the halogen bulb.
Several existing approaches use a large value electrolytic capacitor after the bridge rectifier to smooth the AC waveform. This has also the advantage of keeping an output voltage higher than the forward voltage of the LEDs and provides a continuous supply voltage (Vcc) for the driver. This approach works really well with 50 Hz transformers and provides power factors of up to 0,65 .Using this method with an electronic transformer will make the LED flicker.
To keep a good power factor we need to get rid of the big electrolytic capacitor after the bridge rectifier. By eliminating this capacitor, a half-sine waveform will be available going from 0V up to $12V\sqrt{2}$. Consequently it will switch the driver on and off unless we can provide a circuit that works down to a 0V input.

One of the solutions is to use a power factor correction stage and then an LED driver, but due to the board size and cost this is not the right approach.

The best solution is to use a buck boost topology with the LM3409 LED driver with constant off time.

With this solution, a 0.98 PF is achievable by using the IADJ pin of the IC connected via a resistor divider to the AC waveform and creating a sine-wave input current that is proportional to the input voltage.
This buck boost topology provides a constant negative forward voltage for the LEDs.
This forward LED voltage is applied to the IC in addition to the input voltage that supplies the driver.
Therefore when the input voltage Vac reaches 0V, the minimum voltage available to the IC is three times the forward voltage of an LED.
When the input voltage reaches its max peak value of $12V\sqrt{2}$, the maximum voltage available to the driver IC is three times the forward voltage of an LED in addition to $12V\sqrt{2}$.
With this approach, we keep the driver always ON even if the input voltage reaches 0V.

Phase dimming may be an option with certain combination of electronic transformer and Triac dimmer.

One more advantage compared to a halogen bulbs is the lifetime, which is over 40 times longer when using LEDs.
To maintain a long lifetime, electrolytic capacitors have not been used. Instead this design uses only tantalum and ceramic capacitors.
The design also enables safe operation during open and short circuit conditions on the LED output.

The main purpose of the power supply is to convert the rectified AC input to DC regulated current for 3 LEDs in series. The power supply provides protection for the LEDs, limits the transient input voltage and protects against inrush current at plug-in. The overall power supply conformity (e.g. mains harmonics (EN), mains interference, international safety standards etc.) have not been tested for all the applicable European Norms (EN).

The heart of this power supply is the constant off time LM3409 LED driver.

The LM3409/09HV are P-channel MosFET (PFET) controllers for step-down (buck) current regulators. They offer wide input voltage range, high-side differential current sense with low adjustable threshold voltage, fast output enable/disable function and a thermally enhanced eMSOP-10 package. These features combine to make the LM3409/09HV ideal for use as constant current sources for driving LEDs where forward currents up to 5A are easily achievable. The LM3409/09Q/09HV/09QHV uses Constant Off-Time (COFT) control to regulate an accurate constant current without the need for external control loop compensation. Analog and PWM dimming are easy to implement and result in a highly linear dimming range with excellent achievable contrast ratios. Programmable UVLO, low-power shutdown, and thermal shutdown complete the feature set.

The report includes the schematic, design description, bill of materials and a full set of performance measurements taken from a prototype unit.
Figure 1 shows a picture of the **4.5W MR16 LED.**
The LED used are Golden Dragon from Osram.
Part number: LCW W5AM

Figure 1:

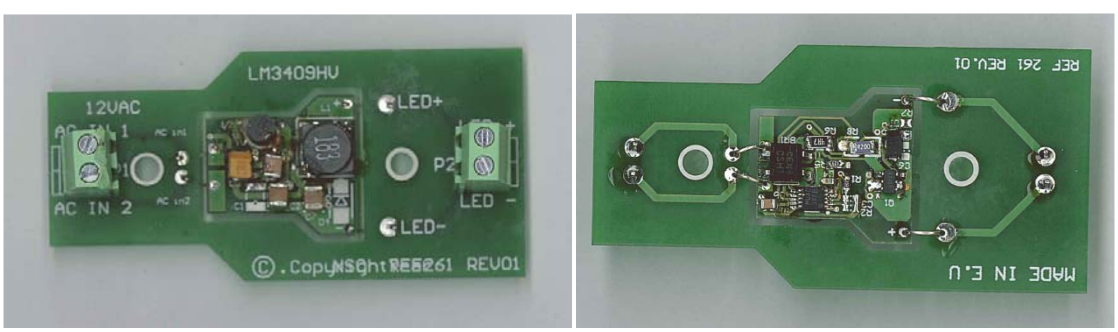
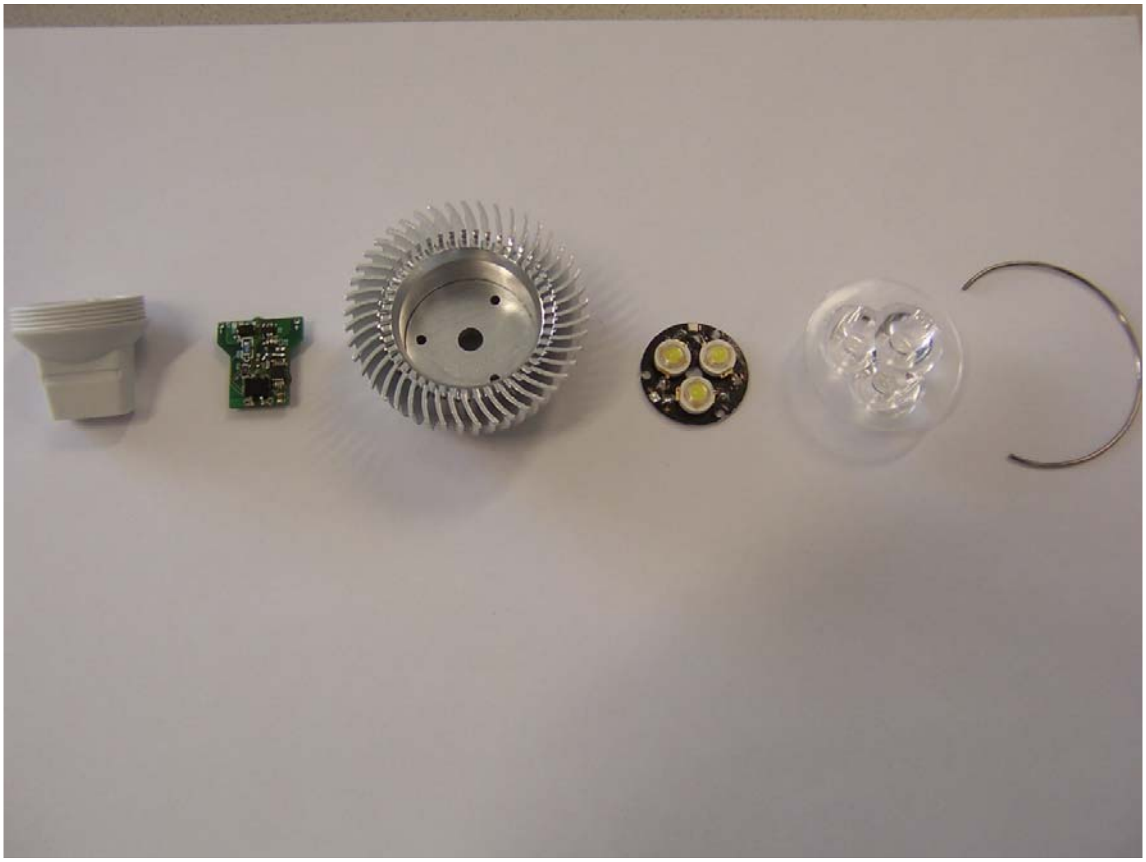
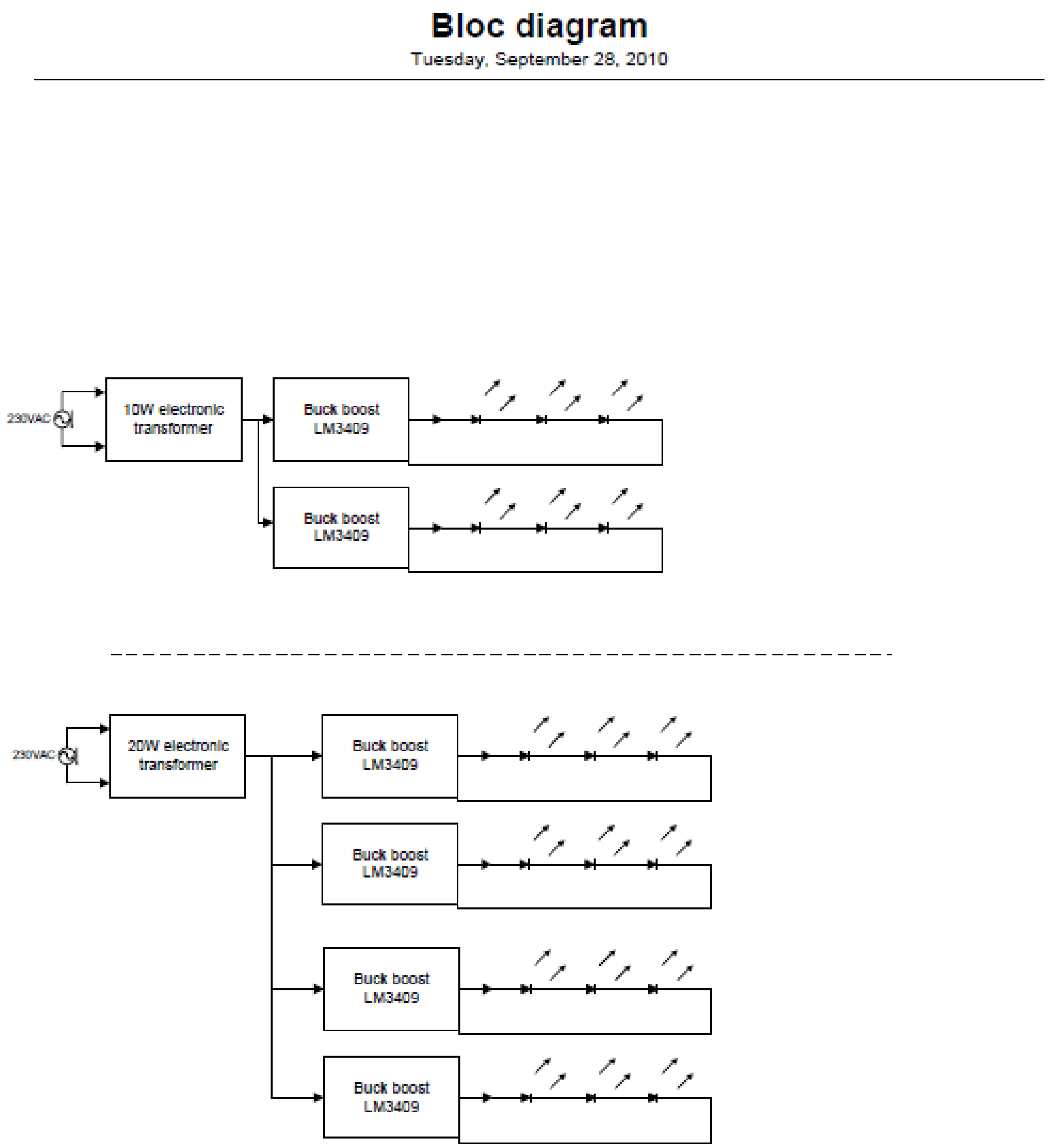


Figure 2 shows the MR16 LED kits.

Figure2:



2 Block diagram



3 Specifications

Specification	Model	**REF 261**
	Max input power (W)	**4.87W**
	DC Output current	**350mA**
	# of LEDs LEDs	**3** **Osram**
Input	Voltage (AC)	**$0V_{AC}$ …..$14\ V_{AC}$**
	PF	**0.94**
	Efficiency (%)	**67%**
Output	Voltage (depending on LED V_F)	**8.8V +/-20%**
	Current (A)	**0.350A**
	Ripple (mA_{pp})	**500mA with 350mA LED current**
	Frequency ripple	**100hz**
	Start up time (ms)	
	Hold up time (input failure)	
	Remote sensing	
	Remote on/off	**Yes, ON/OFF switch**
Isolation	Input/output	**No**
Dimming	With TRIAC Dimmer*	**Yes***
Standards	Safety Agency approvals IEC 61000-3-2 CLASS C	**No** **No**
	EN55015 conduction EN55015 radiation	**No** **No**
Other	Cooling method	**passive**
	Life time	(NO ELCO)
	Temperature range	**-20°C to +…..°C**

Maximum component height is 8 mm. The overall size area is 20mm by 18mm.

*Combination of certain Triac and certain Electronic transformer for dimming.

4 Basic Theory

4.1 Converter Theory

During the time that the PFET (Q1) is turned on (tON), the input voltage charges up the inductor (L1) until reaching the peak current fixed by R8. while the output capacitor (CO) provides energy to the LED .Then Q1 is turned off during a certain time fixed by R5, C4 and forward voltage of the LEDs, the re-circulating diode (D1) becomes forward biased and L1 discharges the energy on the output cap C7 and on the LEDs. During the Ton time the LED current is supplied by the C7. During Toff time the LED current

Figure 1 shows the inductor current on one AC cycle and LED current.
Figure 2 is a zoom of the inductor current on one AC cycle and LED current.

Figure 1.

CH3: Inductor current on L1
CH4: LED current

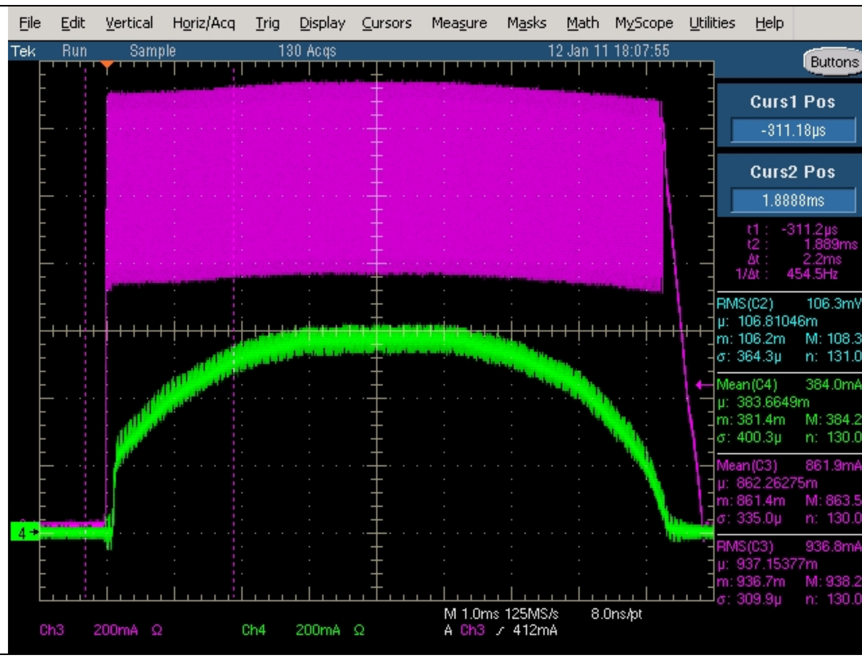
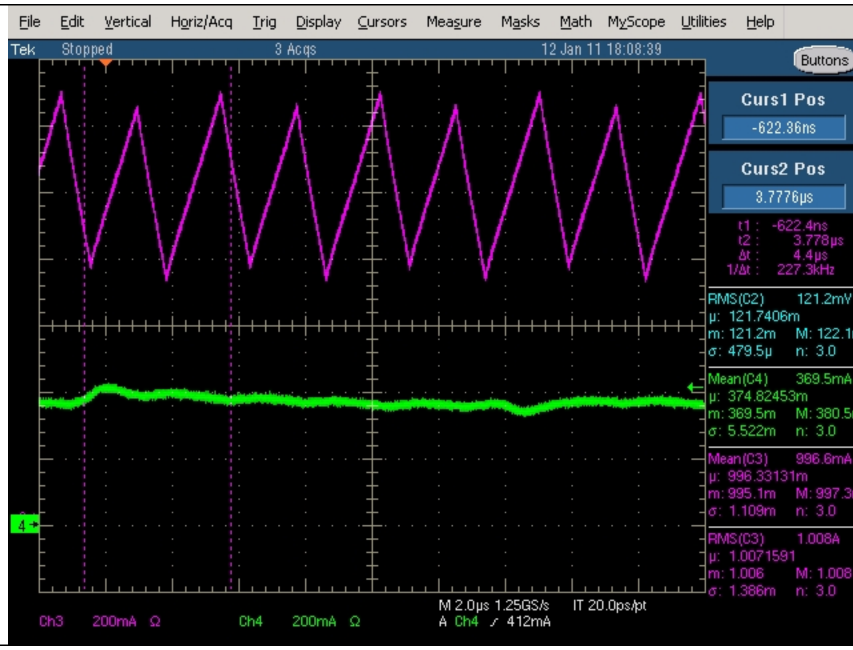


Figure 2.

CH3: Inductor current on L1
CH4: LED current



The output current is proportional to the input voltage waveform, that's why the output current has an AC waveform.
The inductor current equation is:

$$il = \frac{i\,LED}{1-D}$$

So

$$i\,LED = Il * (1-D)$$

Or the duty cycle vary with the input voltage.

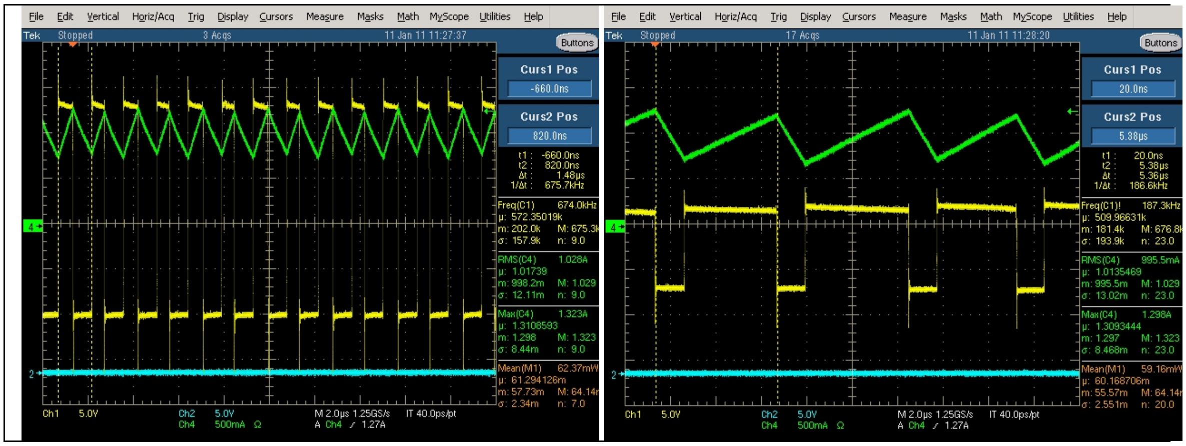
$$D = \frac{3 * VF_{LED}}{V_{in} + 3 * VF_{LED}}$$

Or

$$D = \frac{T_{ON}+T_{OFF}}{T_{ON}}$$

Due to the fact that T_{OFF} is fixed, only T_{ON} will vary with the AC waveform from Vin and therefore the frequency will vary as well. See figure 3
This plots show the drain voltage of Q1and the inductor current in CCM.

Figure 3

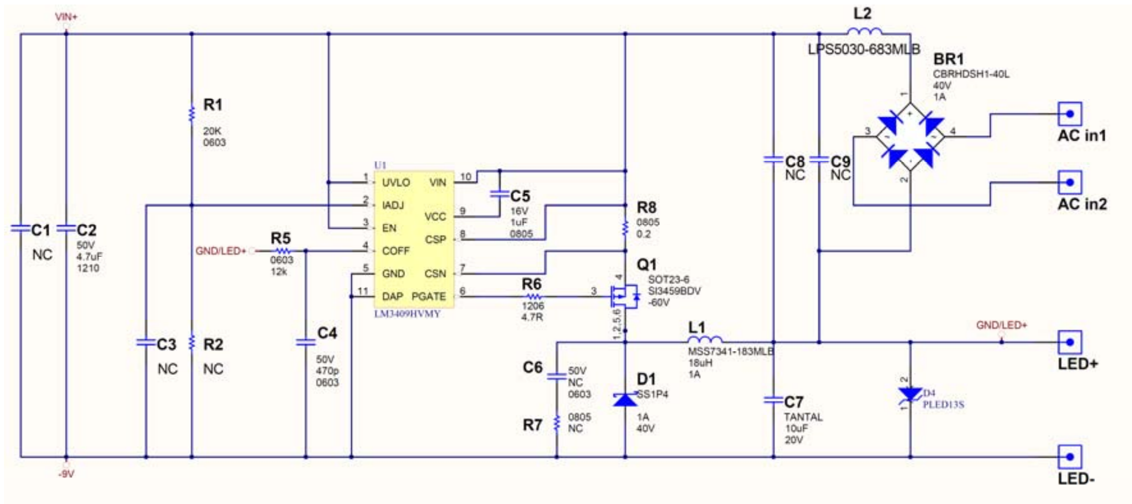


Frequency variation:

……

From 400 KHz to 625 KHz.

5 Schematic



6 Bill of Materials

Bill of Materials

Source Data From:	**LM3409 MR-16.PrjPCB**	
Project:	**REF261**	
Variant:	**None**	
Creation Date:	1/14/2011	2:51:41 PM
Print Date:	26-May-11	11:27:53 AM

Designator	PartNumber	Value	VDC_V	Description	Quantity
BR1	CBRHDSH1-40L		40V 1A	40V, 1A, MiniDIP	1
C2	C1210C475K5RAC	4.7uF	50V	1210	1
C4	C0603C471J5GAC	470p	50V	MLCC, 0603, ?u, ?V, X7R	1
C5	C0805C105K4RAC	1uF	16V	805	1
C7	T491B106K020AS	10uF	20V	MLCC, 1210, ?u, ?V, X7R	1
D1	SS1P4		40V 1A	Schottky, SMA, ?V, ?A	1
D4	PLED13S			Zener Diode	1
L1	MSS7341-183MLB	18uH		Ferrite, Shielded, Drum Core	1
L2	LPS5030-683MLB	68uH			0
Q1	SI3459BDV	-60V		MOSFET, P-CH, -20V, -5.5A, SuperSOT-6	1
R1		20K		Thick Film, 0603, 1%	1
R5		12k		Thick Film, 0603, 1%	1
R6		4.7R		1206	1
R8	RCWL0805R200JQ	0.2		Thick Film, 0805, 1%	1
U1	LM3409HVMY			ET Buck Controller for High Power LED Driv	1
					14

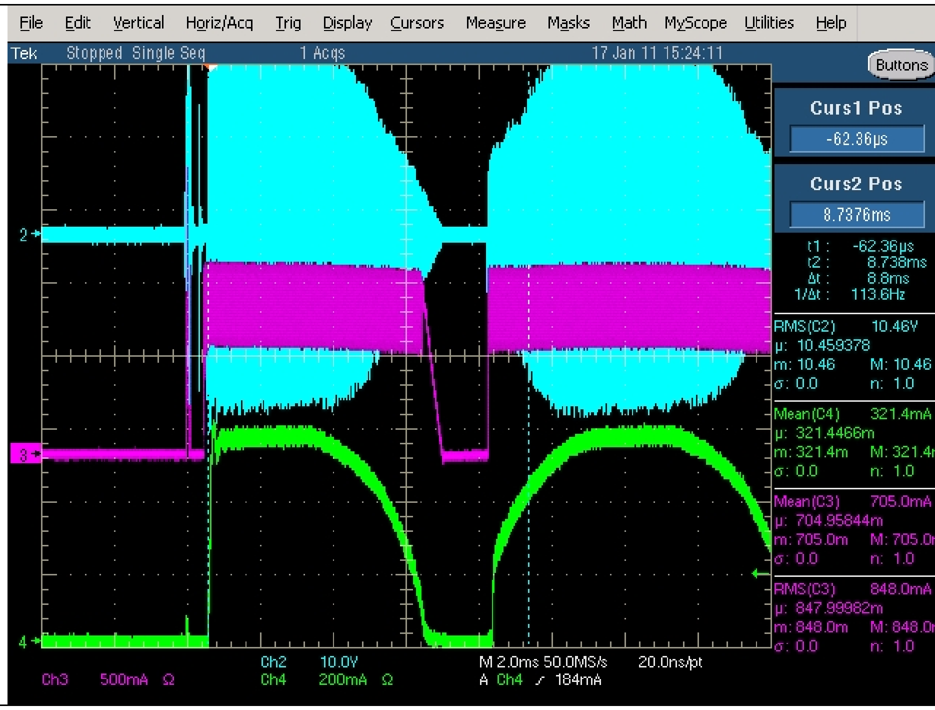
Approved	Notes

7 Start up phase

7.1 Plug in into the network line

CH2: input Voltage
CH3: Inductor current
CH4: LED current

Condition :
Measurement done at hot plug.
$V_{in\ main}$:
230V_{AC}
Output:
3LEDs@0.35A

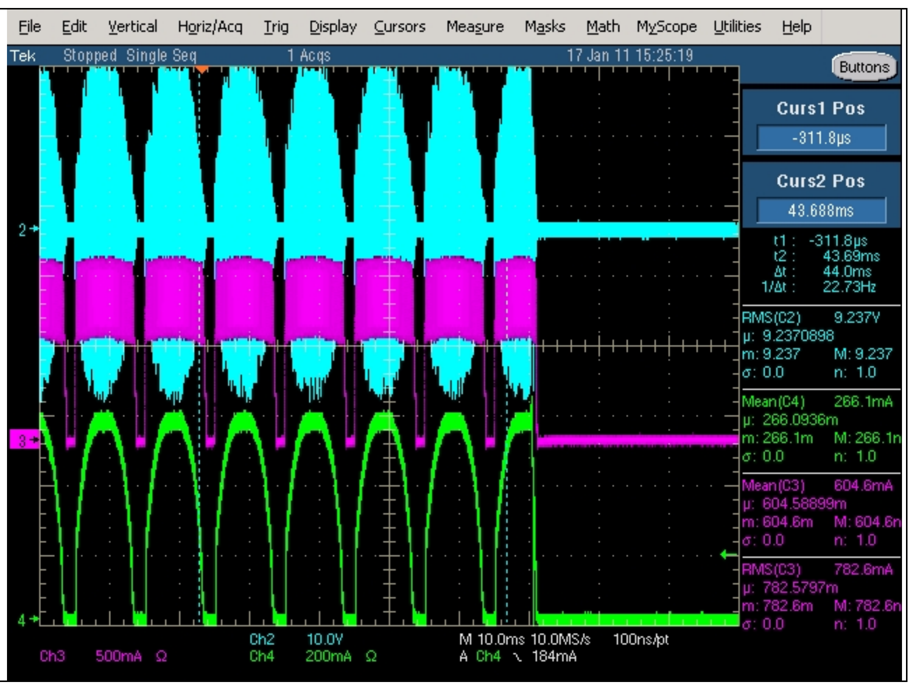


7.2 Holding time

CH2: input Voltage
CH3: Inductor current
CH4: LED current

Condition :
Measurement done at plug out
V_{in}: 230V_{AC}
V_{out}: 3 LEDs @0.35A

Holding time:
0 ms



8 Measurements

8.1 One complete cycle:

This plot shows in detail the drain source voltage and drain current of Q1 for one complete cycle at full power on the LED driver.
The cycle can be divided into different phases as shown on the plot:

1. Switch on phase
2. Conducting phase
3. Switch off phase
4. Off phase, Energy released into the load

8.2 *Input operating waveforms*

The electronic transformer provides a 100 Hz envelope and a switching frequency from 30kHz to160kHz.
At the output of the input filter we see only the envelope.

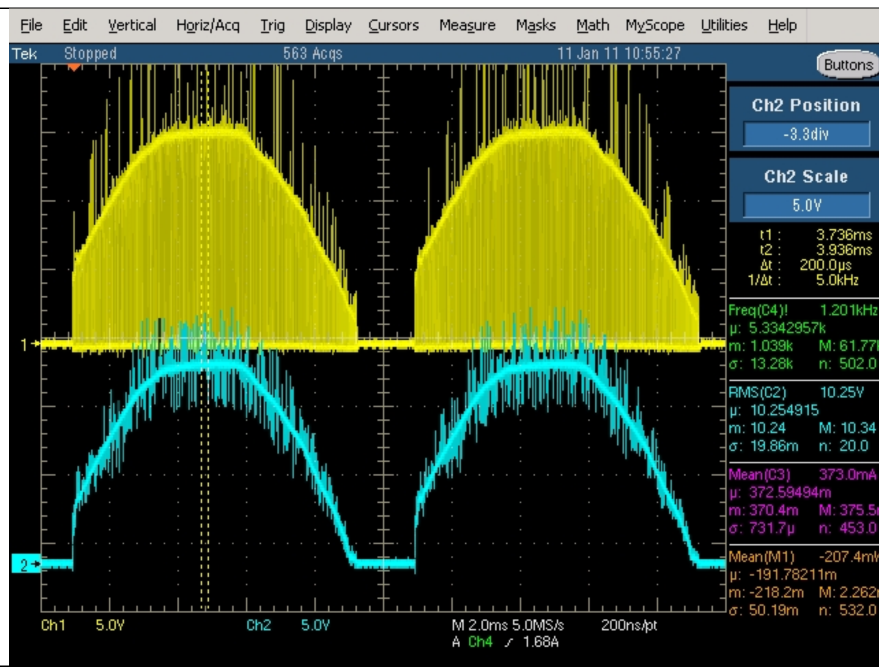
The following plot shows the envelope after the input filter and the bridge rectifier at 230V_{AC}.

8.2.1 Input filter

CH1: Pin 1 of the bridge BR1

CH2: pin C8 +, after the input filter.

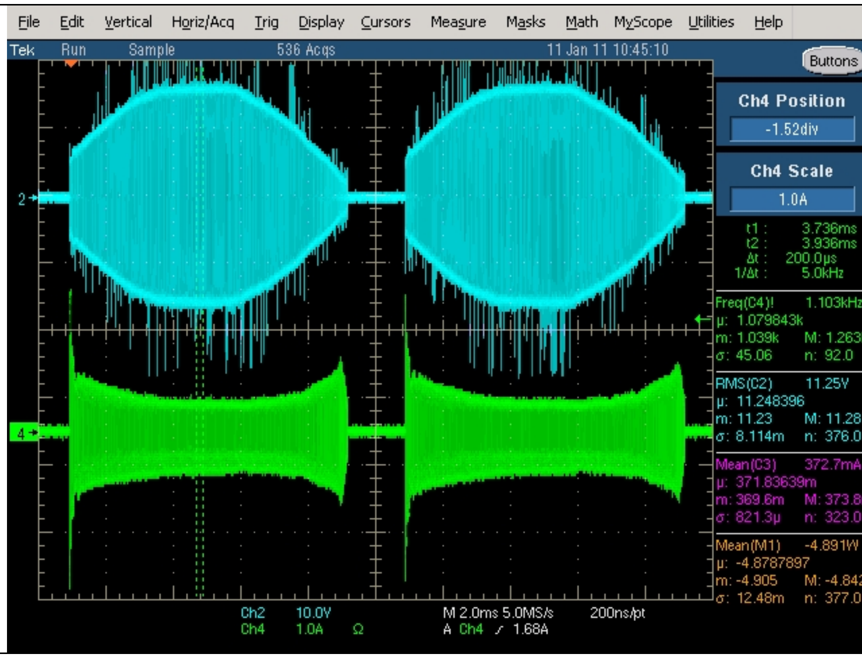
Condition:
$V_{in\ main}$: 230V_{AC}
Output:
3LEDs@0.37A

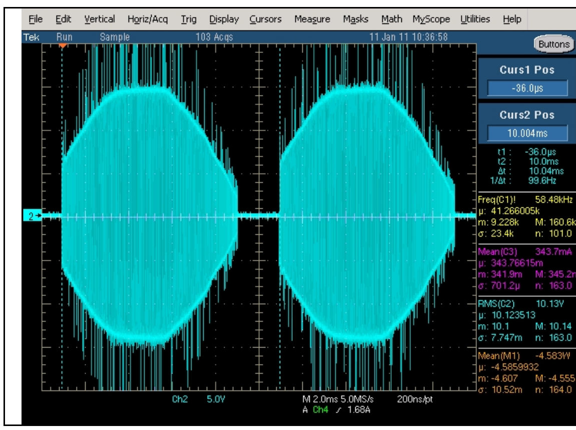


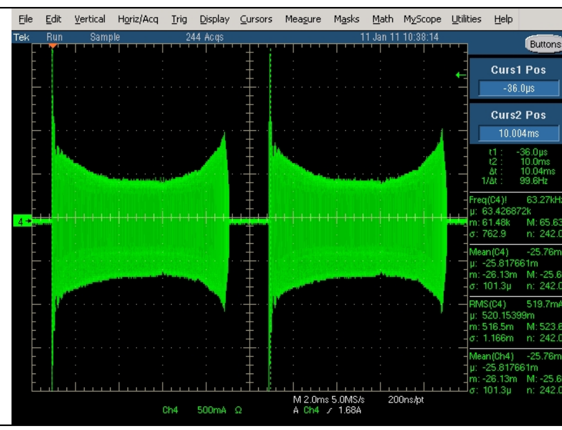
8.3 Main input voltage at 11.5V_{AC} and input current with mains 230Vac.

CH2: Input voltage
CH4: Input current

Condition:
V_{AC}: 11.5V_{AC}
Output : 3 LEDs@0.372A





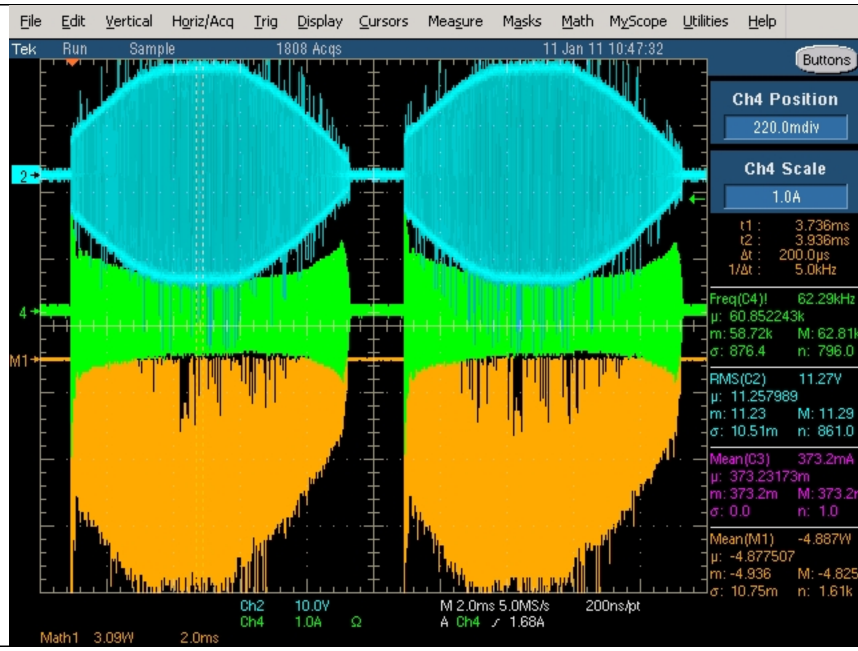


8.4 Power input voltage at 12V_{AC}

Input power: 4.88W for 373mA current LED

CH2: Input voltage
CH4: Input current
M1: Power input

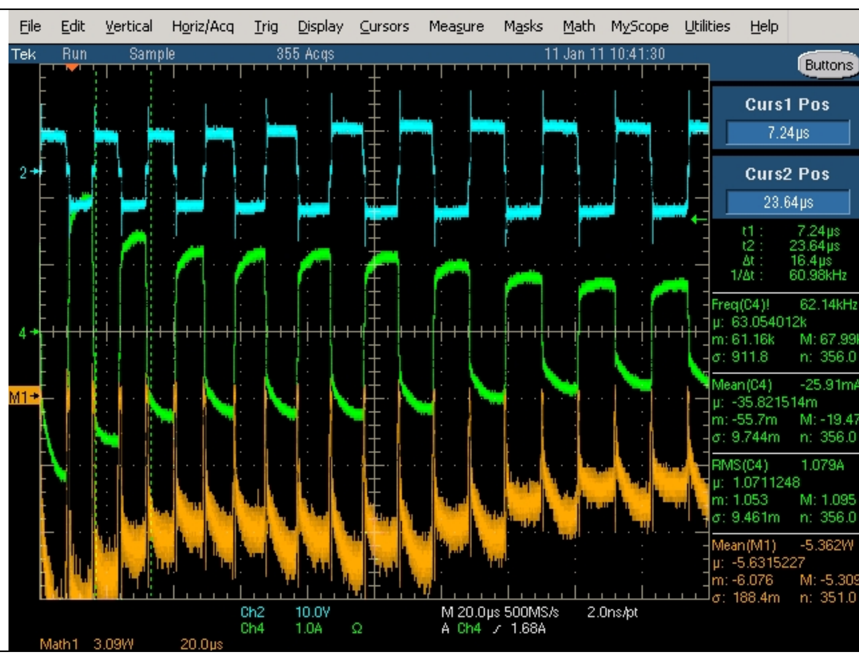
Condition:
$V_{in\ main}$: 230V_{AC}
Output :
3 LEDs@0.35A



ZOOM:

CH2: Input voltage
CH4: Input current
M1: Power input

Condition:
$V_{in\ main}$: 230V_{AC}
Output :
3 LEDs@0.35A

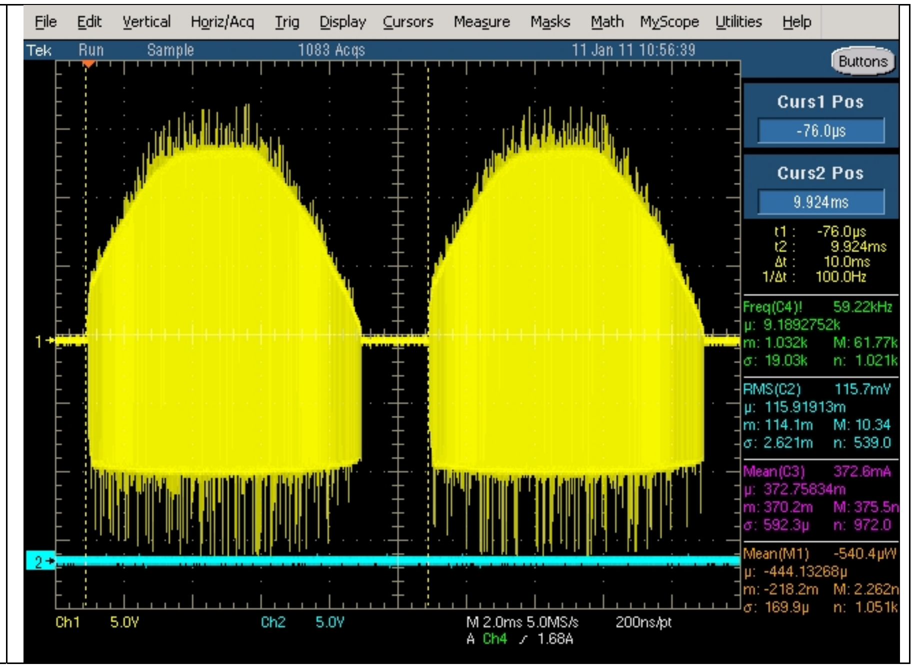


8.4.1 Switching node

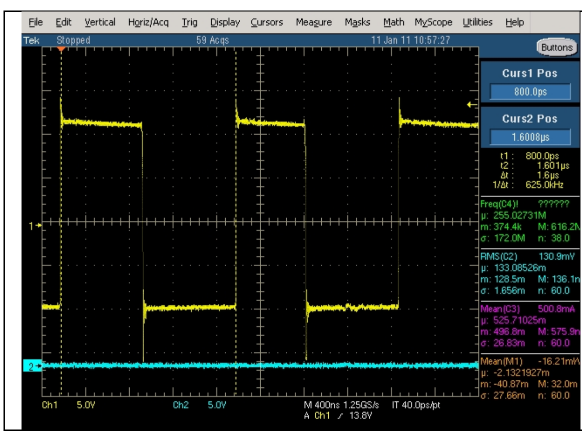
Due to the fact that the GND of the oscilloscope is GND/LED+ or GND of the bridge rectifier, the drain voltage has a negative waveform due to the LED- which is the ground of the driver.

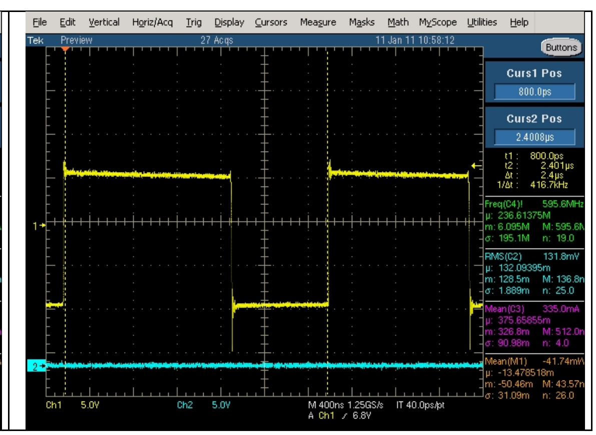
CH1: Drain voltage Q1

Condition:
$V_{in\ main}$: 230V_{AC}
Output:
3LEDs@0.37A



Zoom with min and max input voltage
Frequency variation from 400 KHz to 625 KHz.
Toff keeps constant.





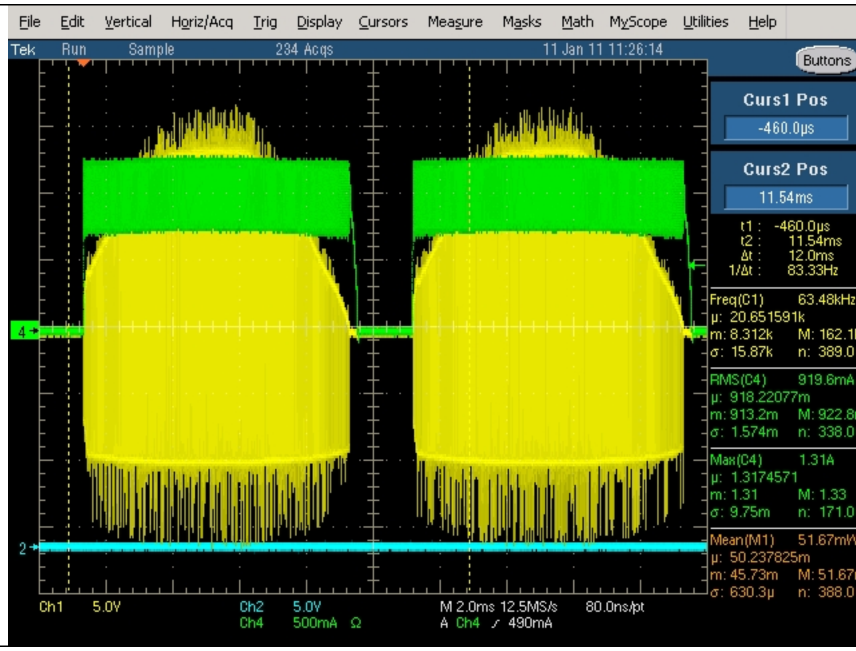
8.4.2 Inductor current

The inductor current is constant because we regulate on the peak current of the inductor.

CH1: Drain voltage Q1

CH4: Inductor current

Condition:
$V_{in\ main}$: 230V_{AC}
Output:
3LEDs@0.37A



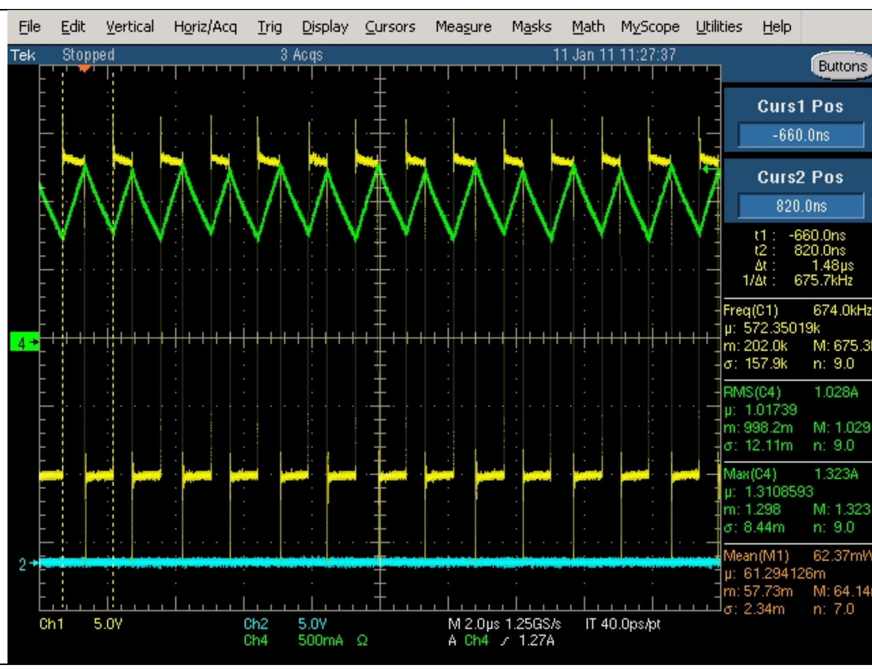
8.4.3 Zoom of the drain and current inductor

The following plot shows the drain voltage and the inductor current at min and max input voltage after the electronic transformer.

CH1: Drain voltage Q1

CH4: Inductor current

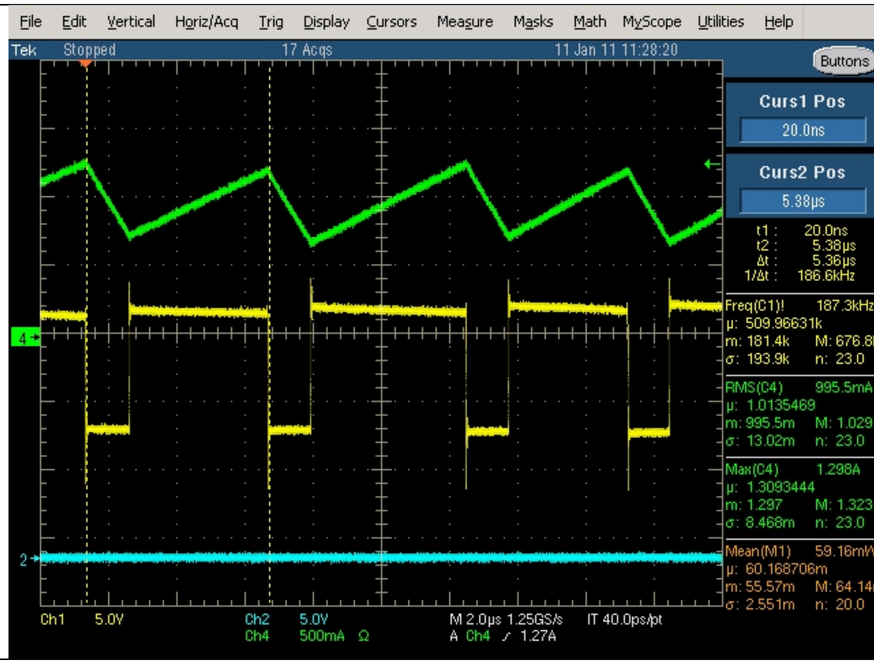
Condition:
$V_{in\ main}$: 230V_{AC}
Vin : 12Vmax
Output:
3LEDs@0.37A



CH1: Drain voltage Q1

CH4: Inductor current

Condition:
$V_{in\ main}$: 230V_{AC}
Vin : 2Vmin low Vin
Output: 3LEDs@0.37A



8.5 *LED driver waveform*

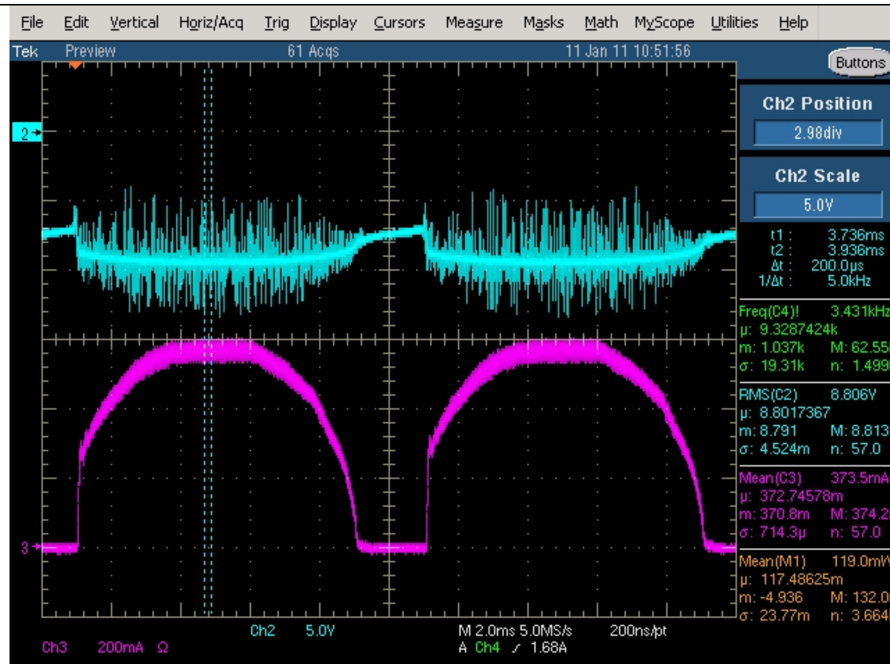
The LM3409 operates by regulating the peak current in the buck inductor L1.

8.5.1 LED current and voltage

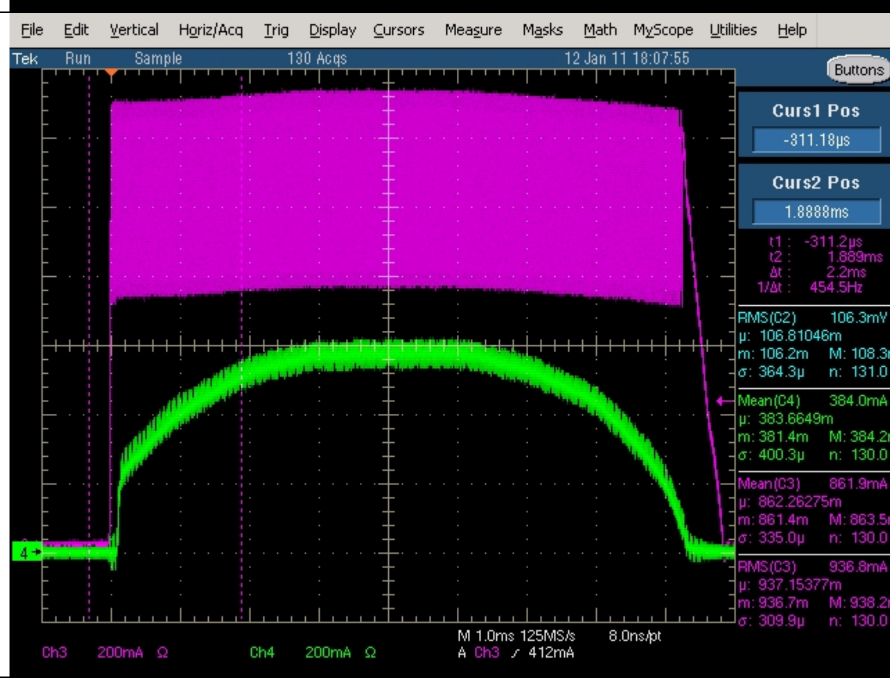
CH2: 8.8Vdc
CH3:LED current

Peak to peak ripple equal to 600mA

LED ave: 373mA



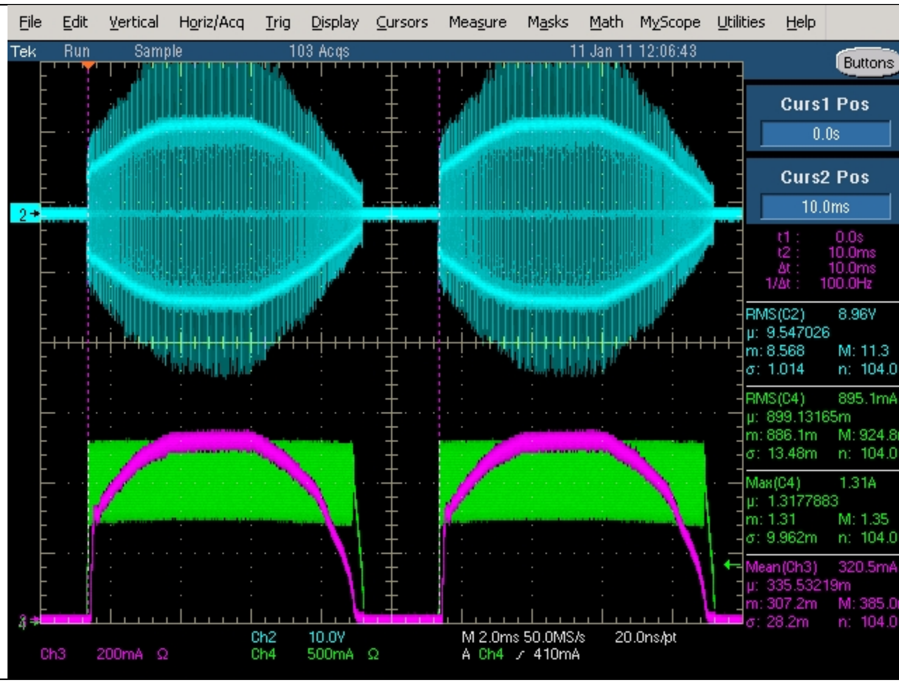
CH2: Inductor current
CH3:LED current



8.5.2 LED current with Vin variation (min, nom and max)

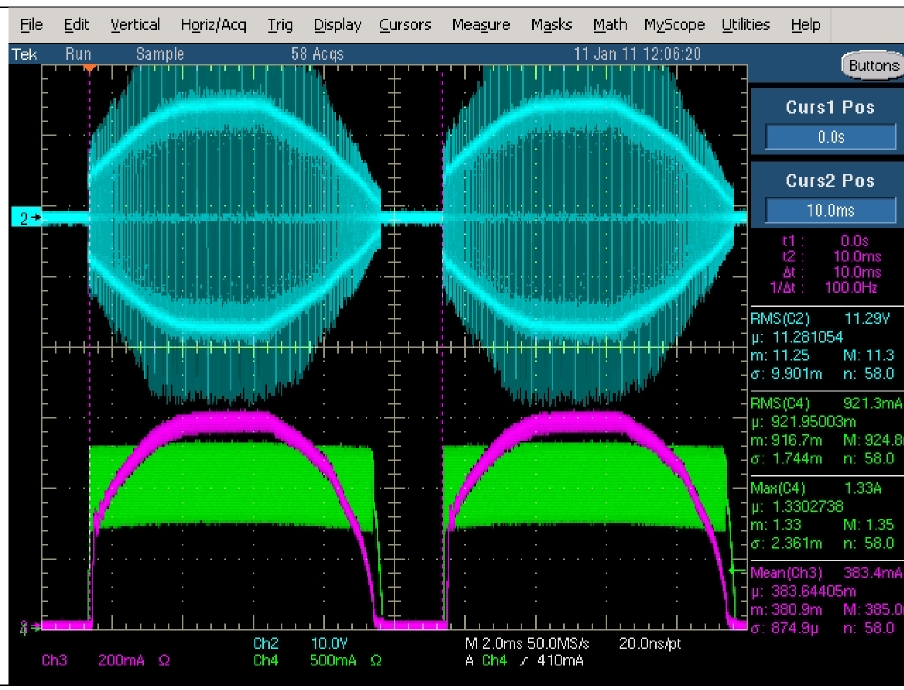
CH2: AC input (8.96Vrms)
CH4: Inductor current
CH3:LED current 0.32A

Condition:
Vin Main: 185VAC
Vin : 8.96Vrms



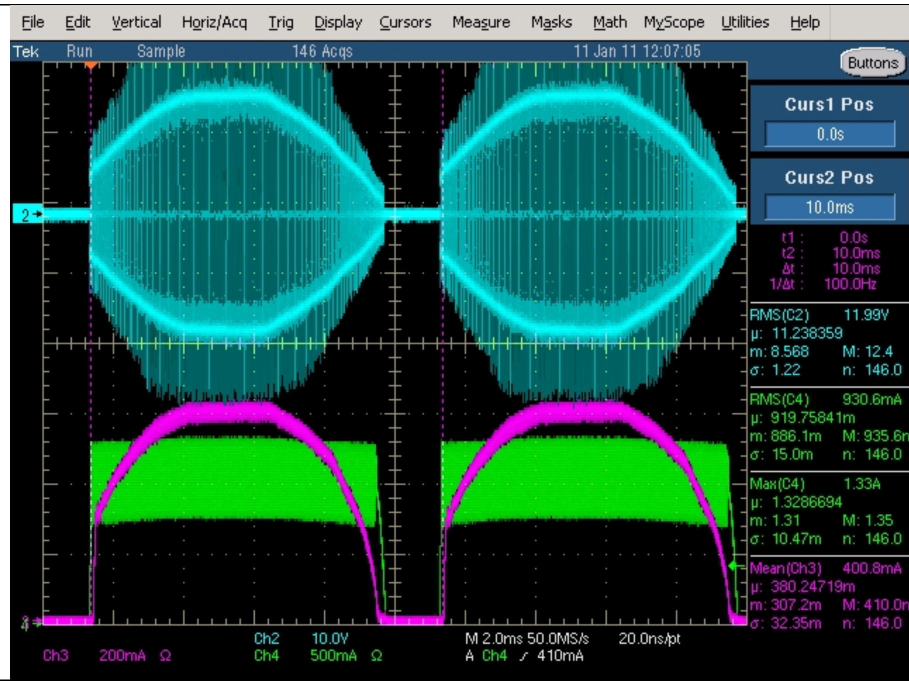
CH2: AC input (11.3Vrms)
CH4: Inductor current
CH3:LED current 0.38A

Condition:
Vin Main: 230VAC
Vin : 11.3Vrms



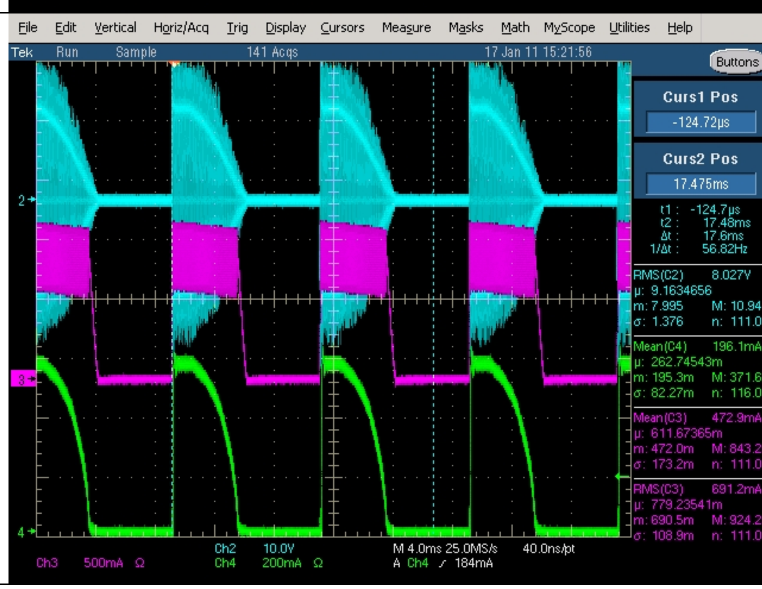
CH2: AC input (12Vrms)
CH4: Inductor current
CH3:LED current 0.40A

Condition:
Vin Main: 245VAC
Vin : 12Vrms



8.6 Dimming

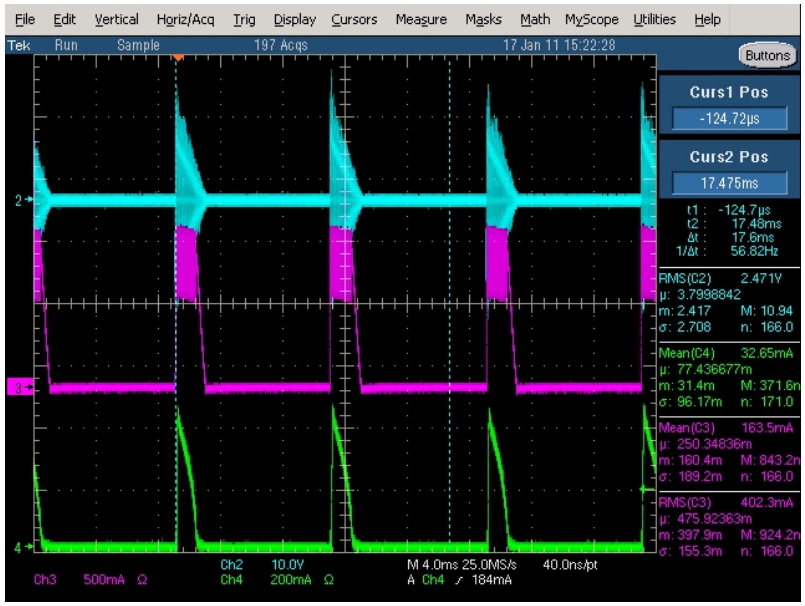
As we mention on the introduction the dimming need to be optimized, by selecting the input filter.
It can be dimmable by with the appropriate Triac and electronic transformer.
The following test has been done using a Triac dimmer EMD200, 40w…300w from Everfloorish, the electronic transformer is from Relco Sugar 60 , RN1578, 10W..60W.
We used 4 MR16 minimum to make it dimmable otherwise it will flicker.

CH2: AC input (12Vrms) **CH3:** Inductor current **CH4:**LED current 0.38A Condition: Vin Main: 230VAC Vin : 11.37Vrms Full dimming	
CH2: AC input (8Vrms) **CH3:** Inductor current **CH4:**LED current 0.19A Condition: Vin Main: 230VAC Vin : 8Vrms 50% dimming	

CH2: AC input (2.47Vrms)
CH3: Inductor current
CH4:LED current 0.032A

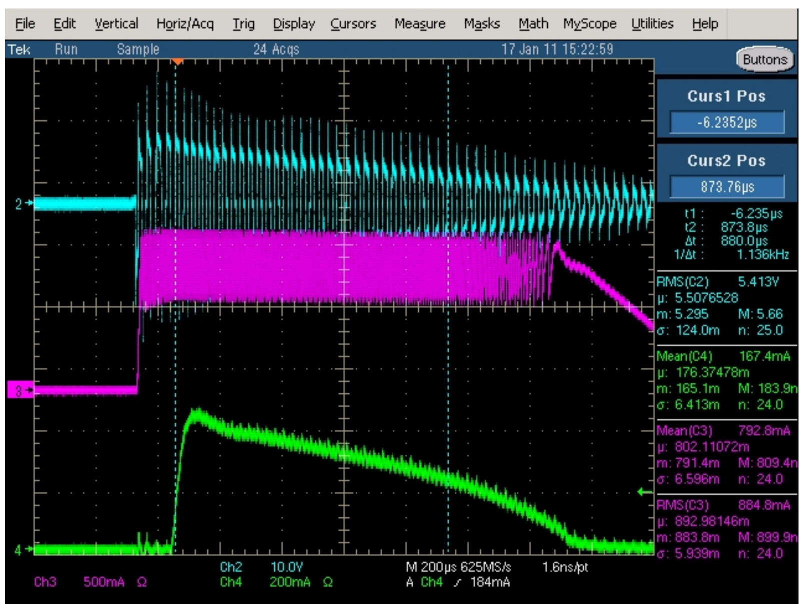
Condition:
Vin Main: 230VAC
Vin : 2.47Vrms

Low dimming



Zoom:
CH2: AC input (2.47Vrms)
CH3: Inductor current
CH4:LED current 0.032A

Condition:
Vin Main: 230VAC
Vin : 2.47Vrms
Low dimming



9 Protection

For safety reasons and to fulfill short circuit requirements, it has been ensured that no component should overheat and burn in case of short circuit.
The short circuit test has been done before and after plug in.

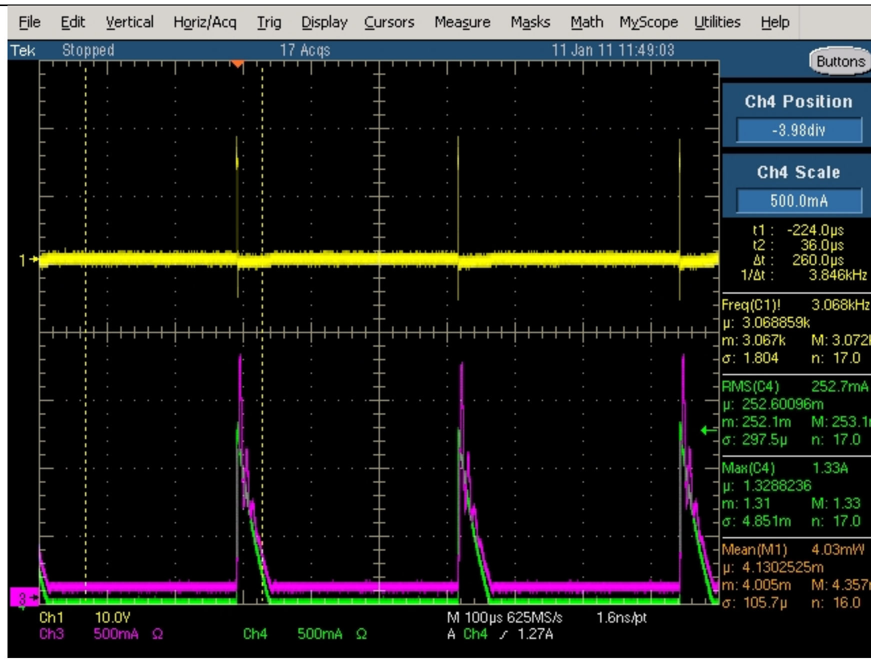
9.1.1 Short circuit protection

The cycle by cycle current limiting controls the maximum power in case of short circuit or an excessive load.

The following plots show a typical protection after short circuit on the LEDs.

CH1: drain voltage Q1
CH3: LED current
CH4: Inductor current

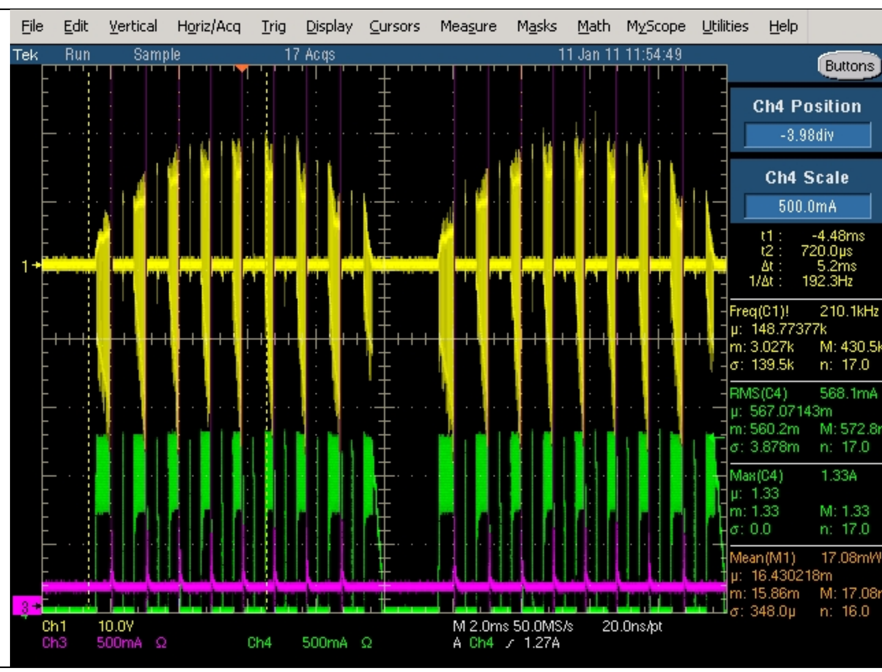
Condition:
SHORT CIRCUIT
No TRIAC dimmer
Vin main:230V_{AC}

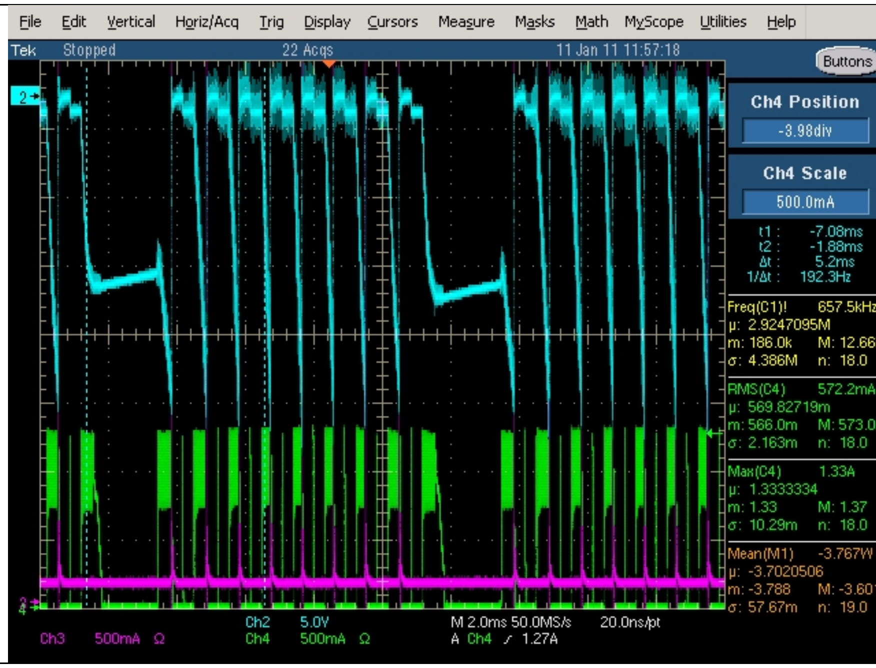


As soon as the short circuit is removed from the output, the power supply will go back to the regulated current 350mA.

9.1.2 Open LED protection

The open LED protector (PLED13Q) provides a switching electronic shunt path when a LED is open circuit to limit the output to increase dramatically.

CH1: drain voltage Q1 **CH3:** LED current **CH4:** Inductor current Condition: **Open loop** No TRIAC dimmer Vin main:230V_{AC}	

CH1: Output voltage on the LED string **CH3:** LED current **CH4:** Inductor current Condition: **Open loop** No TRIAC dimmer Vin main:230V_{AC}	

9.2 Efficiency

Due to the fact that we use a buck boost topology, a rectified bridge for high switching frequency an input filter and a small form factor, we can assume a low efficiency.
The efficiency may differ from electronic transformer.
The input power measured is 4.87W at 230VAC main.
The output power is 3.27W into the LEDs.
8.8V * 372ma =3.27W

EFF: 0.67%

9.3 Thermal behavior

Tests have been done with AC input voltage from 180 VAC to 245VAC with an output current of 365mA over a temperature range from -20°C to +45°C.
The temperature measurements have been taken on the key components: Q1, L1, L2, D1 and BR1.
Start up testing has been done at this ambient temperature.

Vin 180V$_{AC}$

Ambient Temperature		-20°C	-10°C	0°C	25°C	45°C	65°C	75°C
Components								
Mosfet	Q1							
Inductor	L1							
Filter	L2							
Diode	D1							
Bridge	BR1							
Output current	Ave(mA)							

Vin 230V$_{AC}$

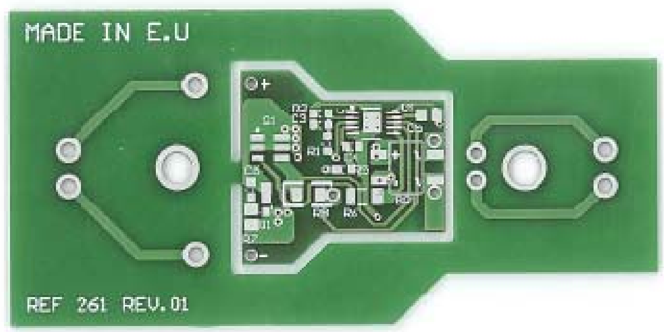
Ambient Temperature		-20°C	-10°C	0°C	25°C	45°C	65°C	75°C
Components								
Mosfet	Q1							
Inductor	L1							
Filter	L2							
Diode	D1							
Bridge	BR1							
Output current	Ave(mA)							

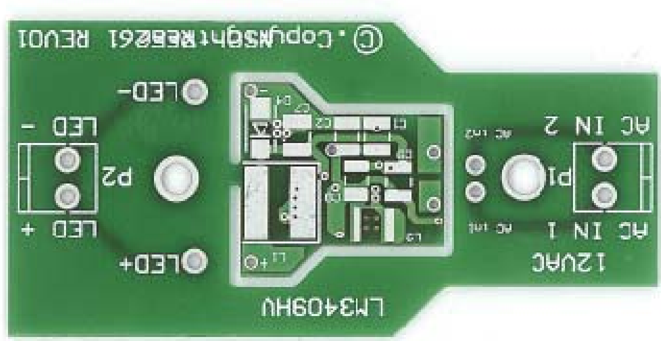
Vin 245V$_{AC}$

Ambient Temperature		-20°C	-10°C	0°C	25°C	45°C	65°C	75°C
Components								
Bleeder	Q1							
Inductor	L1							
Filter	L2							
Diode	D1							
Bridge	BR1							
Output current	Ave(mA)							

10 Layout Design

Top solder and bottom solder.





11 Summary Table

Several investigations need to be done on the input filter to make it run with dimming using different Triac dimmer.

12 Revision History

Status	Date	Description of change (s)
rev02	28/01/2011	L2 = LPS5030-683MLB Polarity on D4 changed on schematic
Rev2.1	07/02/2011	Add Frequency ripple 100hz on specification
Rev 2.2	09/05/2011	Flickers and start up problem solved Bom update.
Rev2.3	25/05/2011	High peak input current solved by L2.

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Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

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DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
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		TI E2E Community Home Page	e2e.ti.com

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