LM3445 - 230VAC, 6W- 15W Isolated Flyback LED Driver

National Semiconductor
Application Note 2069
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Introduction

This demonstration board highlights the performance of a LM3445 based Flyback LED driver solution that can be used to power a single LED string consisting of 4 to 10 series connected LEDs from an 180 V_{RMS} to 265 V_{RMS}, 50 Hz input power supply. The key performance characteristics under typical operating conditions are summarized in this application note.

This is a four-layer board using the bottom and top layer for component placement. The demonstration board can be modified to adjust the LED forward current, the number of series connected LEDs that are driven and the switching frequency. Refer to the LM3445 datasheet for detailed instructions.

A bill of materials is included that describes the parts used on this demonstration board. A schematic and layout have also been included along with measured performance characteristics.

Key Features

- Drop-in compatibility with TRIAC dimmers
- Line injection circuitry enables PFC values greater than 0.94
- Adjustable LED current and switching frequency
- Flicker free operation

Applications

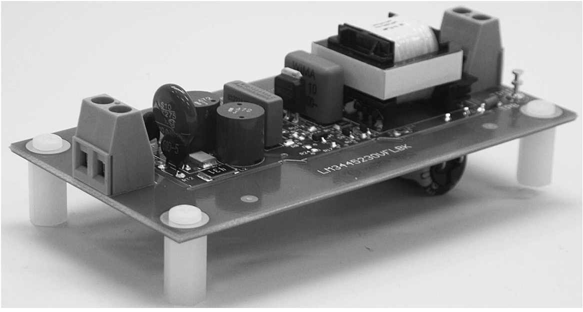
- Retro-fit TRIAC Dimming
- Solid State Lighting
- Industrial and Commercial Lighting
- Residential Lighting

Performance Specifications

Based on an LED V_f = 3.4V

Symbol	Parameter	Min	Typ	Max
V_{IN}	Input voltage	180 V_{RMS}	230 V_{RMS}	265 V_{RMS}
V_{OUT}	LED string voltage	13 V	20 V	27 V
I_{LED}	LED string average current	-	350 mA	-
P_{OUT}	Output power	-	7.2 W	-
f_{sw}	Switching frequency	-	67 kHz	-

Demo Board



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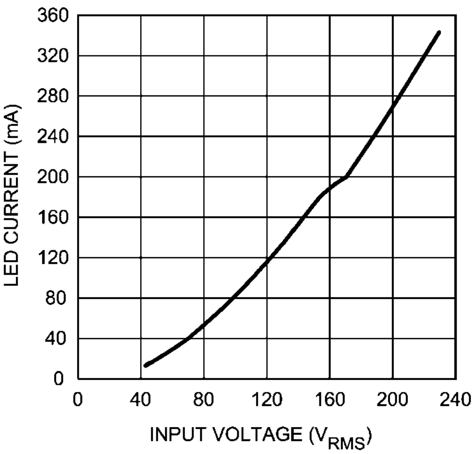
Dimming Characteristics



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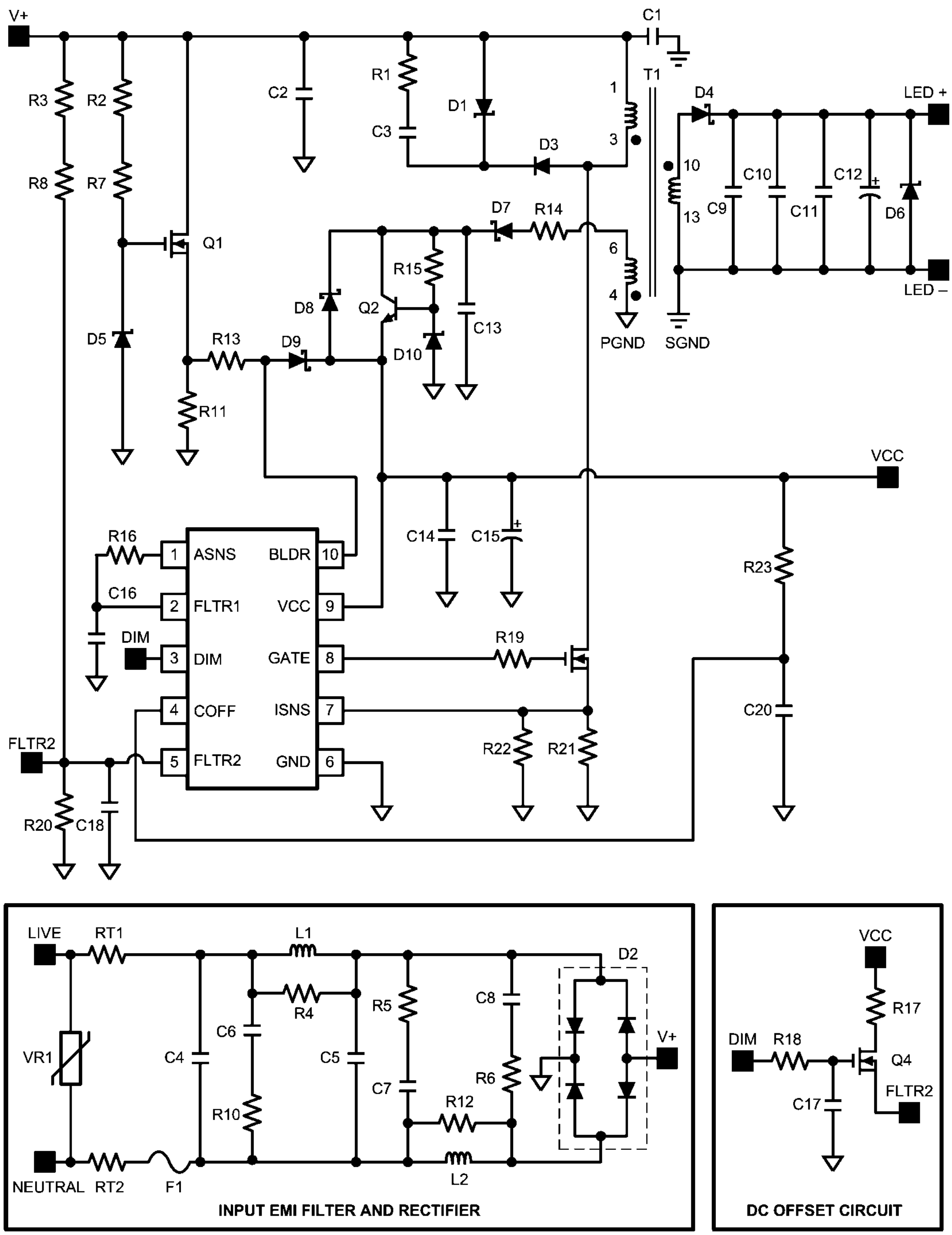
LM3445 230VAC, 8W Isolated Flyback LED Driver Demo Board Schematic



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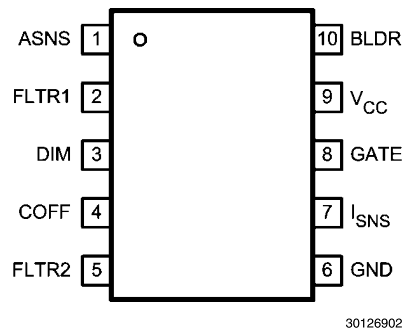
Warning: The LM3445 evaluation board has exposed high voltage components that present a shock hazard. Caution must be taken when handling the evaluation board. Avoid touching the evaluation board and removing any cables while the evaluation board is operating.

Warning: The ground connection on the evaluation board is NOT referenced to earth ground. If an oscilloscope ground lead is connected to the evaluation board ground test point for analysis and the mains AC power is applied (without any isolation), the fuse (F1) will fail open. For bench evaluation, either the input AC power source or the bench measurement equipment should be isolated from the earth ground connection. Isolating the evaliation board (using 1:1 isolation line isolation transformer) rather than the oscilloscope is highly recommended.

Warning: The LM3445 evaluation board should not be powered with an open load. For proper operation, ensure that the desired number of LEDs are connected at the output before applying power to the evaluation board.

LM3445 Device Pin-Out



Pin Description 10 Pin MSOP

Pin #	Name	Description
1	ASNS	PWM output of the triac dim decoder circuit. Outputs a 0 to 4V PWM signal with a duty cycle proportional to the triac dimmer on-time.
2	FLTR1	First filter input. The 120Hz PWM signal from ASNS is filtered to a DC signal and compared to a 1 to 3V, 5.85 kHz ramp to generate a higher frequency PWM signal with a duty cycle proportional to the triac dimmer firing angle. Pull above 4.9V (typical) to tri-state DIM.
3	DIM	Input/output dual function dim pin. This pin can be driven with an external PWM signal to dim the LEDs. It may also be used as an output signal and connected to the DIM pin of other LM3445 or LED drivers to dim multiple LED circuits simultaneously.
4	COFF	OFF time setting pin. A user set current and capacitor connected from the output to this pin sets the constant OFF time of the switching controller.
5	FLTR2	Second filter input. A capacitor tied to this pin filters the PWM dimming signal to supply a DC voltage to control the LED current. Could also be used as an analog dimming input.
6	GND	Circuit ground connection.
7	ISNS	LED current sense pin. Connect a resistor from main switching MOSFET source, ISNS to GND to set the maximum LED current.
8	GATE	Power MOSFET driver pin. This output provides the gate drive for the power switching MOSFET of the buck controller.
9	V_{CC}	Input voltage pin. This pin provides the power for the internal control circuitry and gate driver.
10	BLDR	Bleeder pin. Provides the input signal to the angle detect circuitry as well as a current path through a switched 230Ω resistor to ensure proper firing of the triac dimmer.

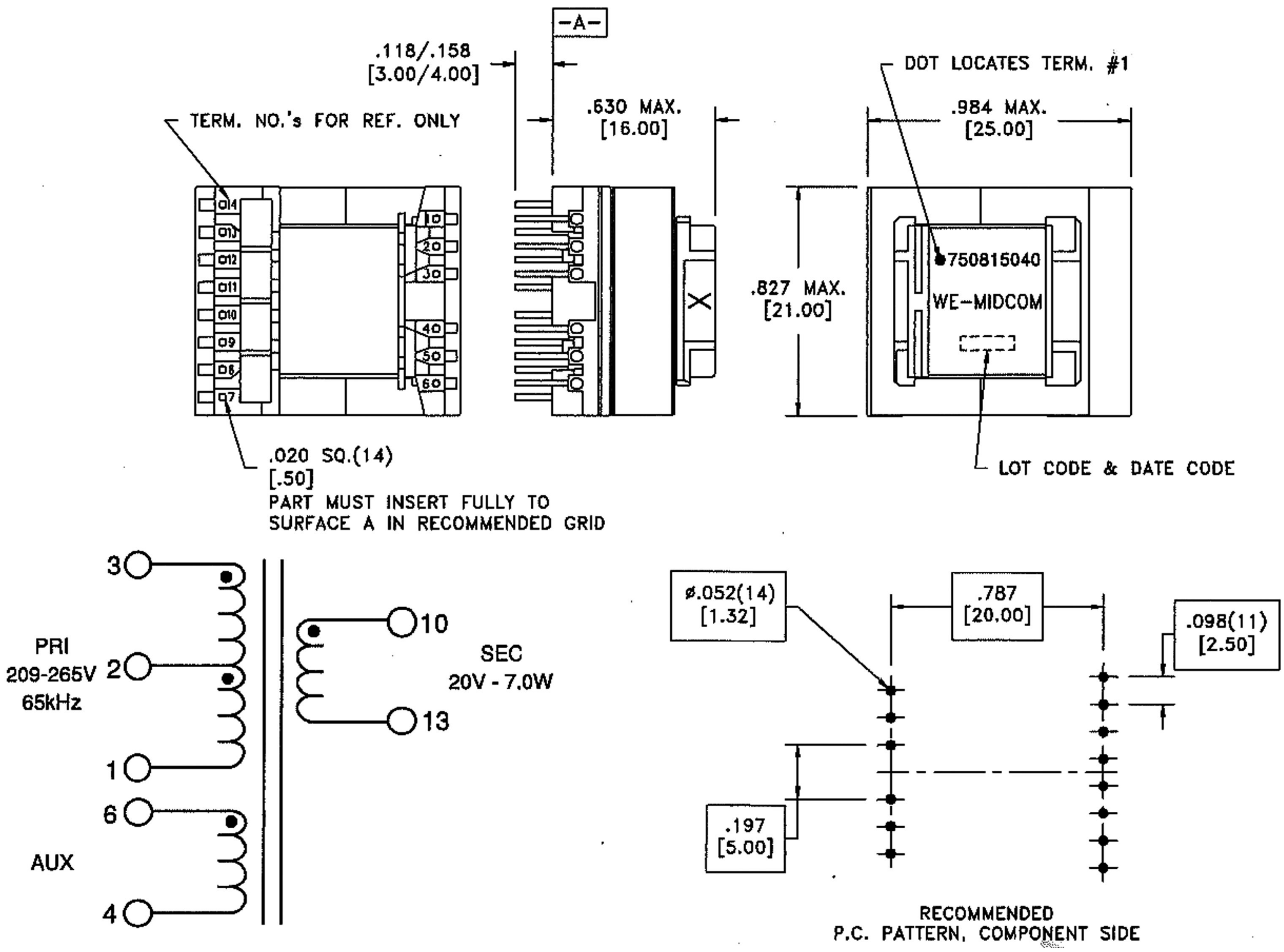
Bill of Materials

Designator	Description	Manufacturer	Part Number	RoHS
AA1	Printed Circuit Board		-	Y
U1	Triac Dimmable Offline LED Driver, PowerWise	National Semiconductor	LM3445MM	Y
C1	Ceramic, X7R, 250VAC, 10%	Murata Electronics North America	DE1E3KX332MA5BA01	Y
C2	Ceramic, Polypropylene, 400VDC, 10%	WIMA	MKP10-.033/400/5P10	Y
C3	CAP, CERM, 330pF, 630V, +/-5%, C0G/NP0, 1206	TDK	C3216C0G2J331J	Y
C4	Ceramic, X7R, 250V, X2, 10%, 2220	Murata Electronics North America	GA355DR7GF472KW01L	Y
C5	CAP, Film, 0.033µF, 630V, +/-10%, TH	EPCOS Inc	B32921C3333K	Y
C6	CAP, CERM, 0.015µF, 500V, +/-10%, X7R, 1812	Vishay/Vitramon	VJ1812Y223KBEAT4X	Y
C7-DNP	CAP, CERM, 0.1µF, 630V, +/-10%, X7R, 1812	MuRata	GRM43DR72J104KW01L	Y
C8	CAP, CERM, 0.1µF, 630V, +/-10%, X7R, 1812	MuRata	GRM43DR72J104KW01L	Y
C9, C11	CAP, CERM, 1µF, 50V, +/-10%, X7R, 1210	MuRata	GRM32RR71H105KA01L	Y
C10	CAP, CERM, 0.47µF, 50V, +/-10%, X7R, 0805	MuRata	GRM21BR71H474KA88L	Y
C12	Aluminium Electrolytic, 680uF, 35V, 20%,	Nichicon	UHE1V681MHD6	Y
C13	CAP, CERM, 1µF, 35V, +/-10%, X7R, 0805	Taiyo Yuden	GMK212B7105KG-T	Y
C14	CAP, CERM, 0.1µF, 25V, +/-10%, X7R, 0603	MuRata	GRM188R71E104KA01D	Y
C15	CAP, TANT, 47uF, 16V, +/-10%, 0.35 ohm, 6032-28 SMD	AVX	TPSC476K016R0350	Y
C16	CAP, CERM, 0.47µF, 16V, +/-10%, X7R, 0603	MuRata	GRM188R71C474KA88D	Y
C17	CAP, CERM, 0.22µF, 16V, +/-10%, X7R, 0603	TDK	C1608X7R1C224K	Y
C18	CAP, CERM, 2200pF, 50V, +/-10%, X7R, 0603	MuRata	GRM188R71H222KA01D	Y
C20	CAP, CERM, 330pF, 50V, +/-5%, C0G/NP0, 0603	MuRata	GRM1885C1H331JA01D	Y
D1	DIODE TVS 250V 600W UNI 5% SMD	Littelfuse	P6SMB250A	Y
D2	Diode, Switching-Bridge, 600V, 0.8A, MiniDIP	Diodes Inc.	HD06-T	Y
D3	Diode, Silicon, 1000V, 1A, SOD-123	Comchip Technology	CGRM4007-G	Y
D4	Diode, Schottky, 100V, 1A, SMA	STMicroelectronics	STPS1H100A	Y
D5, D10	Diode, Zener, 13V, 200mW, SOD-323	Diodes Inc	DDZ13BS-7	Y
D6	Diode, Zener, 36V, 550mW, SMB	ON Semiconductor	1SMB5938BT3G	Y
D7, D8, D9	Diode, Schottky, 100V, 150 mA, SOD-323	STMicroelectronics	BAT46JFILM	Y
F1	Fuse, 500mA, 250V, Time-Lag, SMT	Littelfuse Inc	0443.500DR	Y
H1, H2, H5, H6	Standoff, Hex, 0.5"L #4-40 Nylon	Keystone	1902C	Y
H3, H4, H7, H8	Machine Screw, Round, #4-40 x 1/4, Nylon, Philips panhead	B&F Fastener Supply	NY PMS 440 0025 PH	Y
J1, J2	Conn Term Block, 2POS, 5.08mm PCB	Phoenix Contact	1715721	Y
L1, L2	Inductor, Radial Lead Inductors, Shielded, 4.7mH, 130mA, 12.20ohm, 7.5mm Radial,	TDK Corporation	TSL0808RA-472JR17-PF	Y
LED+, LED-, TP7, TP8	Terminal, 22 Gauge Wire, Terminal, 22 Guage Wire	3M	923345-02-C	Y
Q1	MOSFET, N-CH, 600V, 200mA, SOT-223	Fairchild Semiconductor	FQT1N60CTF_WS	Y
Q2	Transistor, NPN, 300V, 500mA, SOT-23	Diodes Inc.	MMBTA42-7-F	Y
Q3	MOSFET, N-CH, 650V, 800mA, IPAK	Infineon Technologies	SPU01N60C3	Y
Q4	MOSFET N-CH 100V 170MA SOT23-3	Diodes Inc.	BSS123-7-F	Y
R1	RES, 221 ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW1206221RFKEA	Y
R2, R7	RES, 200k ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW1206200KFKEA	Y
R3, R8	RES, 309k ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW1206309KFKEA	Y

Designator	Description	Manufacturer	Part Number	RoHS
R4, R12	RES, 10k ohm, 5%, 0.25W, 1206	Vishay-Dale	CRCW120610K0JNEA	Y
R5-DNP	RES, 680 ohm, 5%, 1W, 2512	Vishay/Dale	CRCW2512680RJNEG	Y
R6	RES, 820 ohm, 5%, 1W, 2512	Vishay/Dale	CRCW2512820RJNEG	Y
R10	RES, 430 ohm, 5%, 1W, 2512	Vishay/Dale	CRCW2512430RJNEG	Y
R11	RES, 49.9k ohm, 1%, 0.125W, 0805	Vishay-Dale	CRCW080549K9FKEA	Y
R13	RES, 33.0 ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW120633R0FKEA	Y
R14	RES, 10 ohm, 5%, 0.125W, 0805	Vishay-Dale	CRCW080510R0JNEA	Y
R15	RES, 10.0k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW060310K0FKEA	Y
R16	RES, 280k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603280KFKEA	Y
R17	RES, 475k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603475KFKEA	Y
R18	RES, 49.9k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW060349K9FKEA	Y
R19	RES, 10 ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW060310R0JNEA	Y
R20	RES, 1.91k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW06031K91FKEA	Y
R21	RES, 2.70 ohm, 1%, 0.25W, 1206	Panasonic	ERJ-8RQF2R7V	Y
R22	RES, 10.7 ohm, 1%, 0.125W, 0805	Vishay-Dale	CRCW080510R7FKEA	Y
R23	RES, 324k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603324KFKEA	Y
RT1, RT2	Current Limitor Inrush, 60Ohm, 20%, 5mm Raidal	Cantherm	MF72-060D5	Y
T1	FLBK TFR, 2.07 mH, Np=140T, Ns=26T, Na= 20T	Wurth Elektornik	750815040 REV 1	Y
TP9, TP10	Terminal, Turret, TH, Double	Keystone Electronics	1502-2	Y
VR1	Varistor 275V 55J 10mm DISC	EPCOS Inc	S10K275E2	Y

Transformer Design

Mfg: Wurth Electronics, Part #: 750815040 Rev. 01



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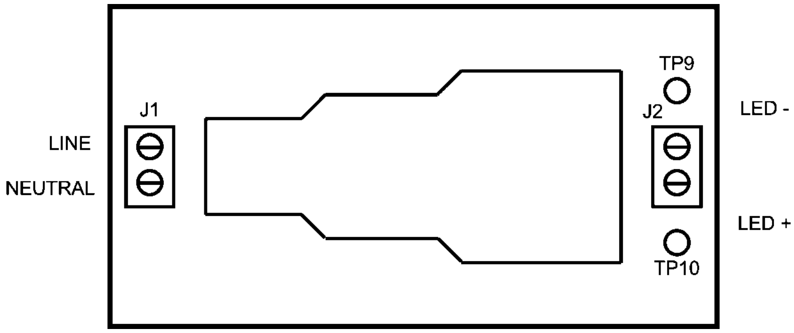
Parameter	Test Conditions	Value
D.C. Resistance (3-1)	20°C	1.91 Ω ± 10%
D.C. Resistance (6-4)	20°C	0.36 Ω ± 10%
D.C. Resistance (10-13)	20°C	0.12 Ω ± 10%
Inductance (3-1)	10 kHz, 100 mVAC	2.12 mH ± 10%
Inductance (6-4)	10 kHz, 100 mVAC	46.50 µH ± 10%
Inductance (10-13)	10 kHz, 100 mVAC	74.00 µH ± 10%
Leakage Inductance (3-1)	100 kHz, 100 mAVAC (tie 6+4, 10+13)	18.0 µH Typ., 22.60 µH Max.
Dielectric (1-13)	tie (3+4), 4500 VAC, 1 second	4500 VAC, 1 minute
Turns Ratio	(3-1):(6-4)	7:1 ± 1%
Turns Ratio	(3-1):(10:13)	5.384:1 ± 1%

Demo Board Wiring Overview



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Wiring Connection Diagram

Test Point	Name	I/O	Description
TP8, TP10	LED +	Output	**LED Constant Current Supply** Supplies voltage and constant-current to anode of LED string.
TP7, TP9	LED -	Output	**LED Return Connection (not GND)** Connects to cathode of LED string. Do NOT connect to GND.
J1-1	LINE	Input	**AC Line Voltage** Connects directly to AC line or output of TRIAC dimmer of a 230VAC system.
J1-2	NEUTRAL	Input	**AC Neutral** Connects directly to AC neutral of a 230VAC system.

Demo Board Assembly

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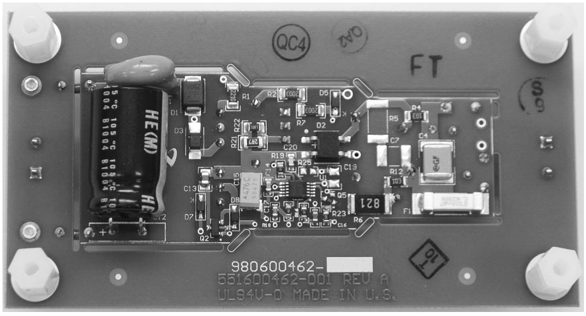
Top View



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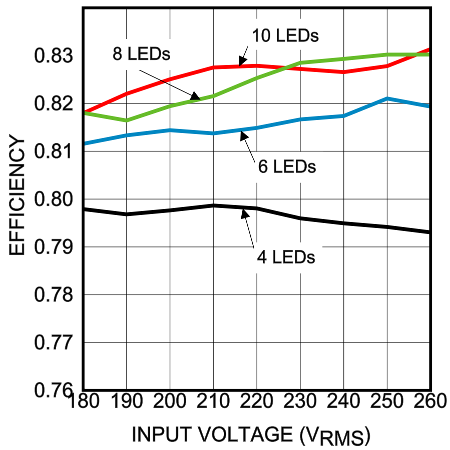
Bottom View

Typical Performance Characteristics (*Note 1*, *Note 2*, *Note 3*)

Efficiency vs. Line Voltage
Original Circuit



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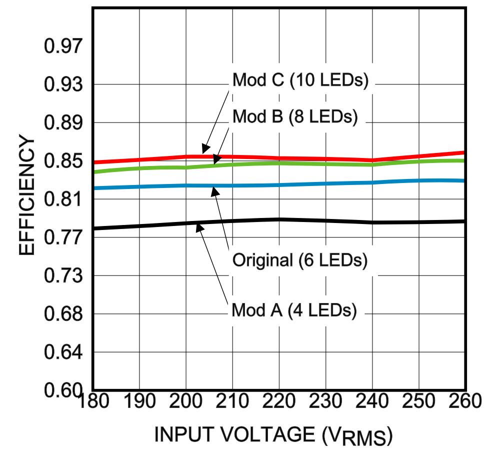
Efficiency vs. Line Voltage
Modified Circuits



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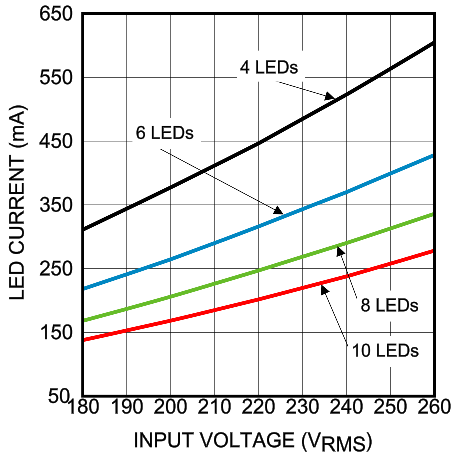
LED Current vs. Line Voltage
Original Circuit



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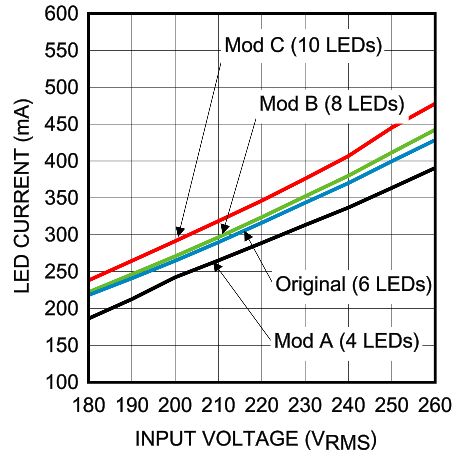
LED Current vs. Line Voltage
Modified Circuits



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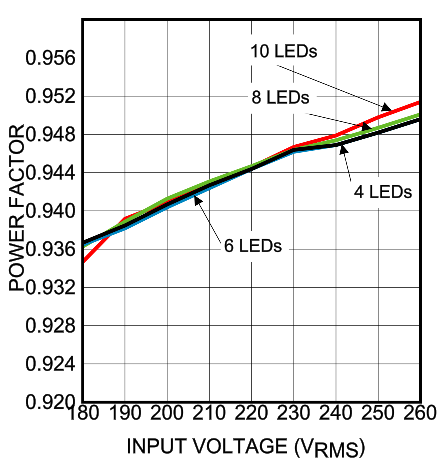
Power Factor vs. Line Voltage
Original Circuit



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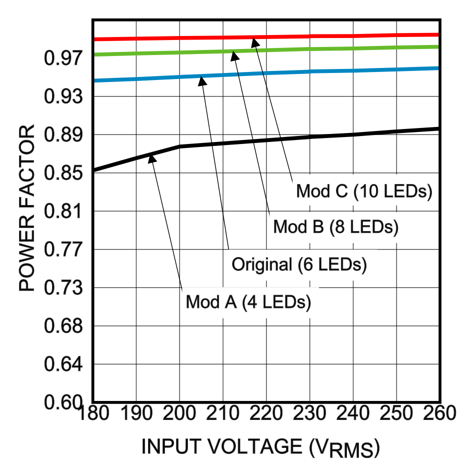
Power Factor vs. Line Voltage
Modified Circuits



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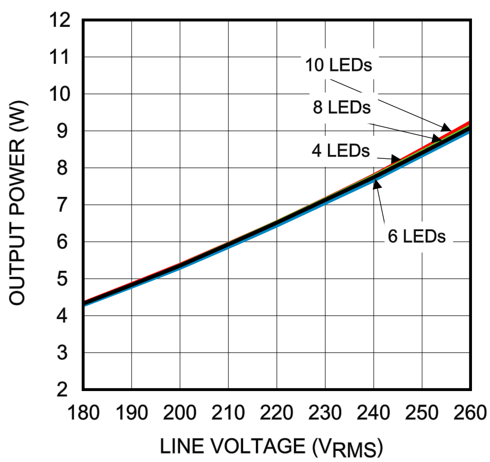
Output Power vs. Line Voltage
Original Circuit



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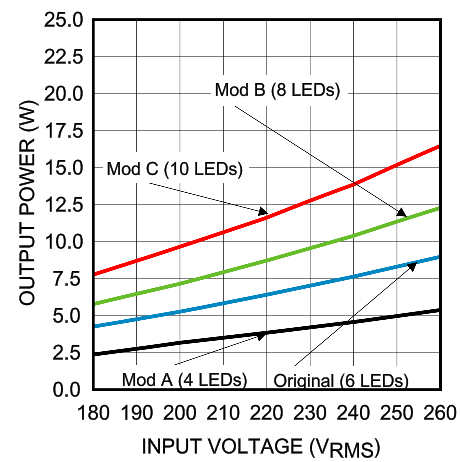
Output Power vs. Line Voltage
Modified Circuits



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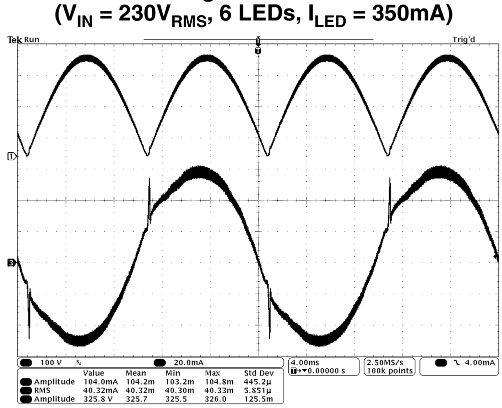
Line Voltage and Line Current
(V_{IN} = 230V_{RMS}, 6 LEDs, I_{LED} = 350mA)



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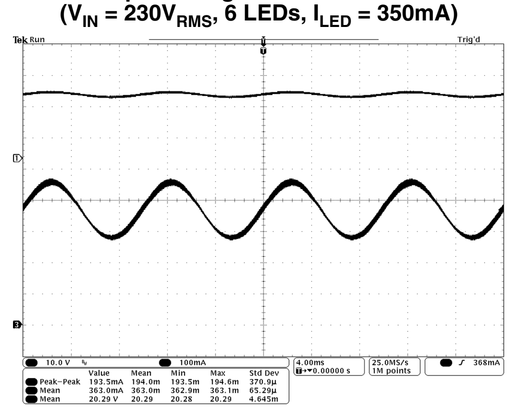
Ch1: Line Voltage (100 V/div); Ch3: Line Current (20 mA/div); Time (4 ms/div)

Output Voltage and LED Current
(V_{IN} = 230V_{RMS}, 6 LEDs, I_{LED} = 350mA)



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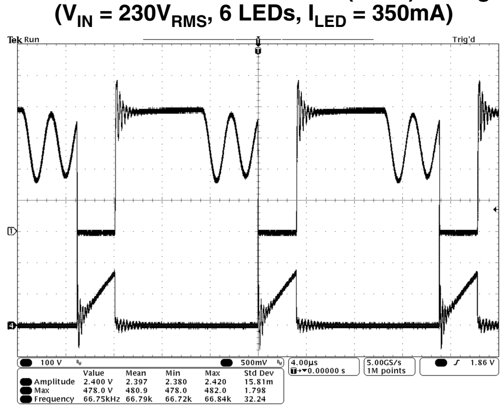
Ch1: Output Voltage (10 V/div); Ch3: LED Current (100 mA/div); Time (4 ms/div)

Power MOSFET Drain and ISNS (Pin-7) Voltage
(V_{IN} = 230V_{RMS}, 6 LEDs, I_{LED} = 350mA)



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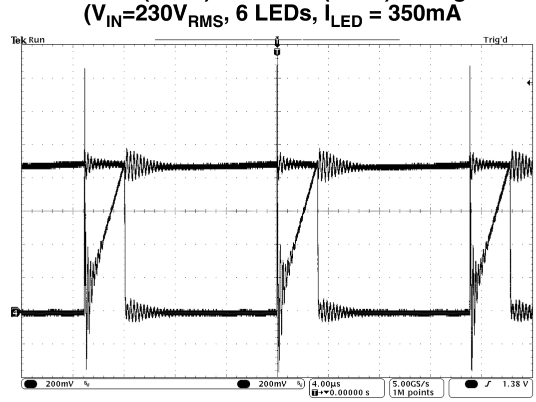
Ch1: Drain Voltage (100V/div); Ch4: ISNS Voltage (500 mV/div); Time (4 µs/div)

FLTR2 (Pin-5) and ISNS (Pin-7) Voltage
(V_{IN}=230V_{RMS}, 6 LEDs, I_{LED} = 350mA



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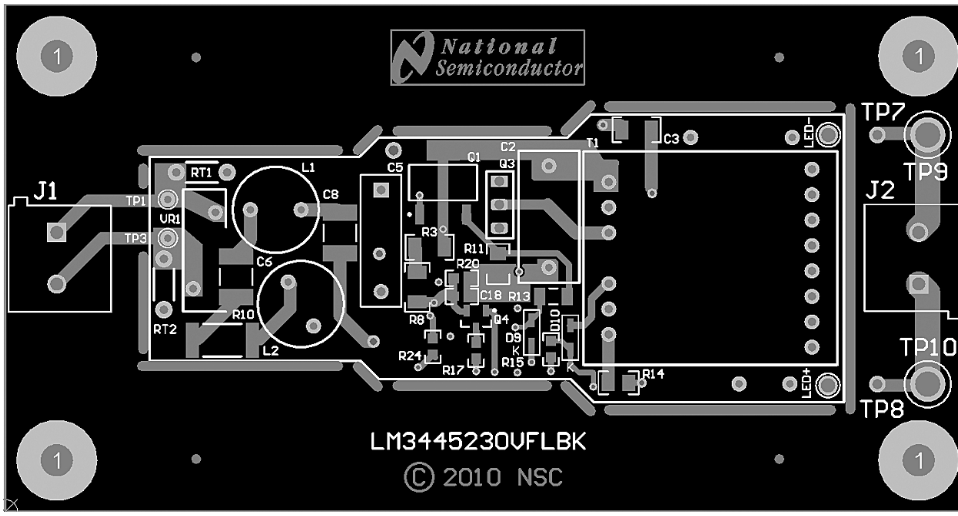
Ch1: FLTR2 Voltage (200 mV/div); ISNS Voltage (200 mV/div); Time (4 µs/div)

Note 1: Original Circuit (6 LEDs operating at 350mA): R21 = 2.7Ω; Modification A (10 LEDs operating at 375mA): R21 = 1.8Ω; Modification B (8 LEDs operating at 350mA): R21 = 2.2Ω; Modification C (4 LEDs operating at 315mA): R21 = 3.9Ω

Note 2: The output power can be varied to acheive desired LED current by interpolating R14 values between the maximum of 3.9 Ω and minimum of 1.8 Ω

Note 3: The maximum output voltage is clamped to 36 V. For operating LED string voltage > 36 V, replace D6 with suitable alternative

PCB Layout



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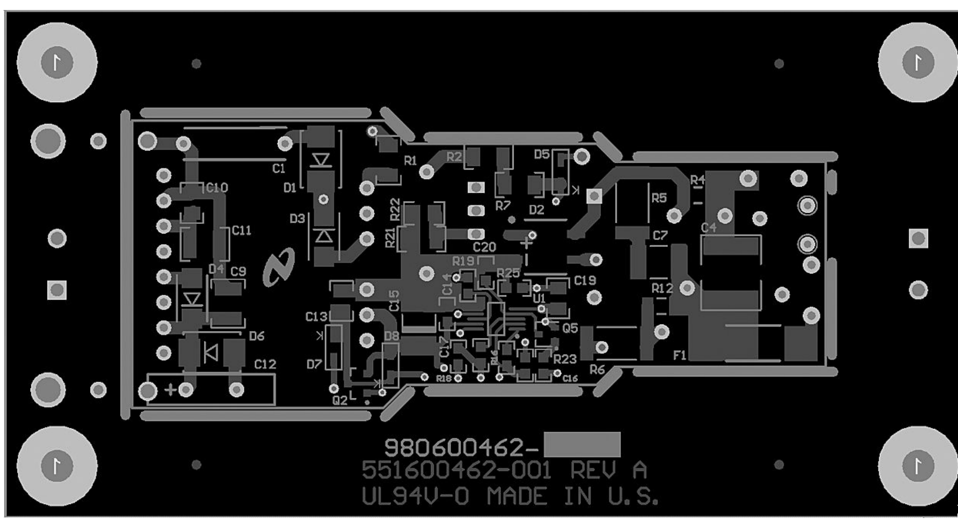
Top Layer



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Bottom Layer

Experimental Results

The LED driver is designed to accurately emulate an incandescent light bulb and therefore behave as an emulated resistor. The resistor value is determined based on the LED string configuration and the desired output power. The circuit then operates in open-loop, with a fixed duty cycle based on a constant on-time and constant off-time that is set by selecting appropriate circuit components. Like an incandescent lamp, the driver is compatible with both forward and reverse phase dimmers.

NON-DIMMING PERFORMANCE

In steady state, the LED string voltage is measured to be 20.5 V and the average LED current is measured as 350 mA. The 100 Hz current ripple flowing through the LED string was measured to be 194 mA_{pk-pk} at full load. The magnitude of the ripple is a function of the value of energy storage capacitors connected across the output port and the TRIAC firing angle. The ripple current can be reduced by increasing the value of energy storage capacitor or by increasing the LED string voltage. With TRIAC dimmers, the ripple magnitude is directly proportional to the input power and therefore reduces at lower LED current.

The LED driver switching frequency is measured to be close to the specified 67 kHz. The circuit operates with a constant duty cycle of 0.21 and consumes near 8.75 W of input power. The driver steady state performance for an LED string consisting of 6 series LEDs without using a triac dimmer is summarized in the following table.

MEASURED EFFICIENCY AND LINE REGULATION (6 LEDS, NO TRIAC DIMMER)

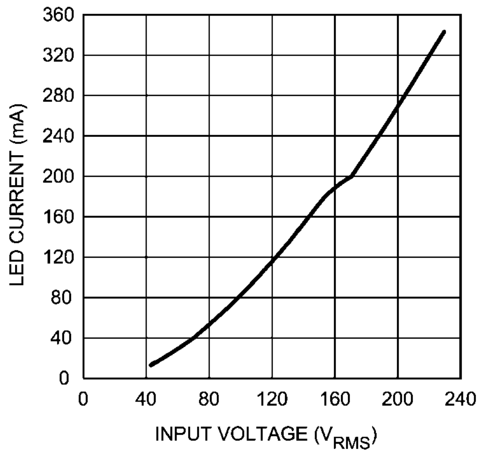
V_{IN} (V_{RMS})	I_{IN} (mA_{RMS})	P_{IN}(W)	V_{OUT} (V)	I_{LED} (mA)	P_{OUT} (W)	Efficiency (%)	Power Factor
180	31.73	5.35	19.67	221.64	4.36	81.4	0.9375
190	33.39	5.96	19.85	244.82	4.86	81.5	0.9394
200	35.11	6.61	20.04	269.16	5.39	81.6	0.9493
210	36.85	7.30	20.22	294.82	5.96	81.6	0.9493
220	38.53	8.01	20.40	321.26	6.55	81.8	0.9451
230	40.18	8.75	20.56	348.70	7.17	82.0	0.9463
240	41.75	9.50	20.74	375.70	7.79	82.0	0.9477
250	43..39	10.30	20.90	404.82	8.46	82.1	0.9490
260	45.07	11.14	21.05	434.48	9.15	82.0	0.9500

DIMMING PERFORMANCE

The LED driver is capable of matching or exceeding the dimming performance of an incandescent lamp. Using a simple rotary TRIAC dimmer, smooth and near logarithmic dimming performance is achieved. By varying the firing angle of the TRIAC dimmer and measuring the corresponding input and output parameters, the dimming performance of the demonstration board driving 6 LEDs is summarized in the table below.

MEASURED DIMMING PERFORMANCE

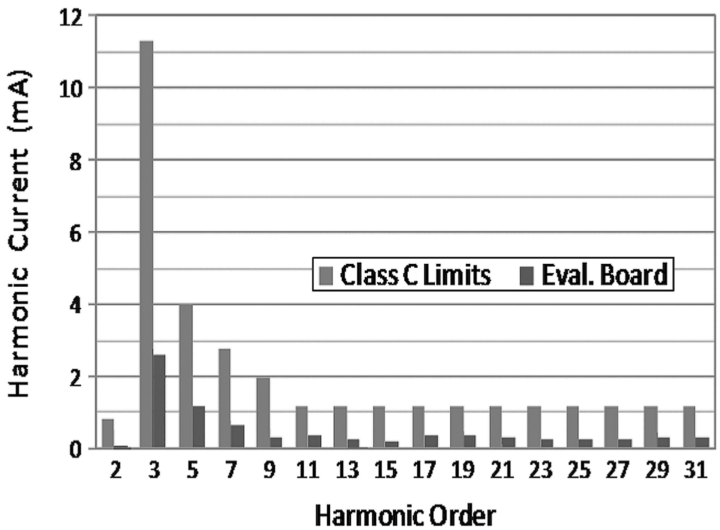
V_{IN} (V_{RMS})	V_O (V)	I_{LED} (mA)	P_{OUT} (W)
229.39	20.51	343.1	7.04
220.47	20.35	320.8	6.53
210.24	20.16	294.8	5.94
199.05	19.98	266.8	5.33
190.32	19.80	245.8	4.87
180.33	19.61	222.7	4.37
170.51	19.42	200.1	3.89
156.39	19.31	187.4	3.62
149.11	19.15	171.6	3.29
140.35	18.97	154.0	2.92
129.61	18.75	133.1	2.50
119.7	18.53	115.3	2.14
110.17	18.33	99.1	1.82
100.55	18.11	83.5	1.51
90.75	17.87	68.8	1.23
79.72	17.59	53.1	0.93
70.42	17.34	40.8	0.71
60.91	17.08	30.1	0.81
49.94	16.77	19.8	0.33
45.04	16.64	16.0	0.27



Dimming Characteristics

CURRENT THD

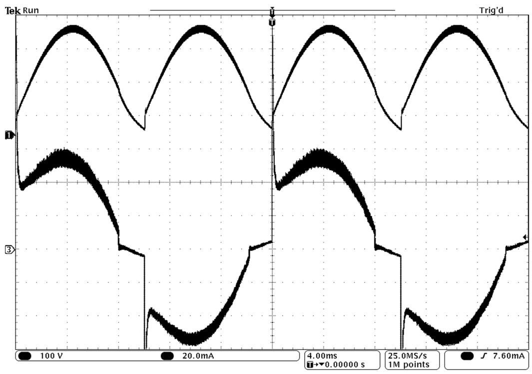
The LED driver is able to achieve close to unity power factor (P.F. ~ 0.94) which meets Energy Star requirements. This design also exhibits low current harmonics as a percentage of the fundamental current (as shown in the following figure) and therefore meets the requirements of the IEC 61000-3-2 Class-3 standard.



Current Harmonic vs. EN/IEC61000-3-2 Class C Limits

Circuit Operation With Rotary Forward Phase Triac Dimmer

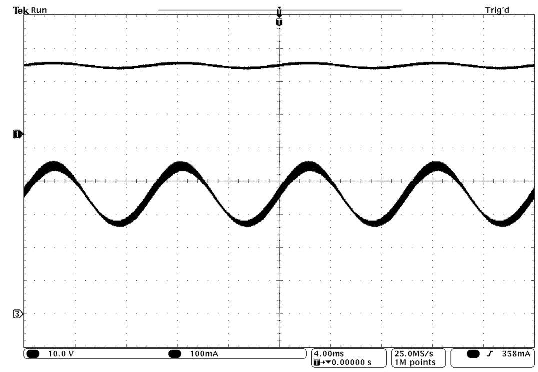
Input waveforms at full brightness setting



30126925

Ch1: Input Voltage (100 V/div); Ch3: Input Current (20 mA/div); Time (4 ms/div)

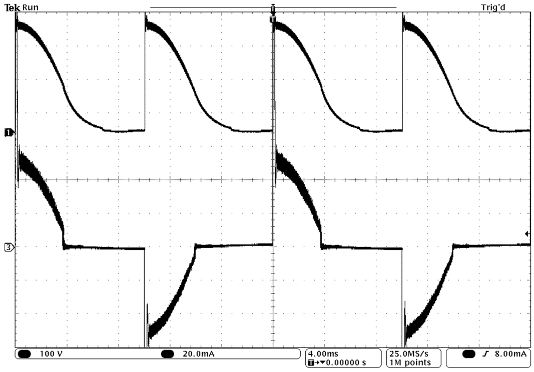
Output waveforms at full brightness setting



30126928

Ch1: Output Voltage (10 V/div); LED Current (100 mA/div); Time (4 ms/div)

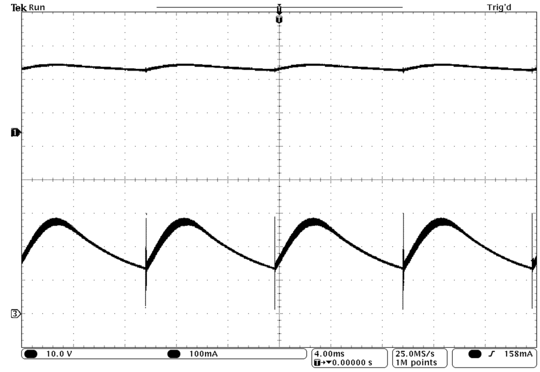
Input waveforms at half brightness setting (90° firing angle)



30126926

Ch1: Input Voltage (100 V/div); Ch3: Input Current (20 mA/div); Time (4 ms/div)

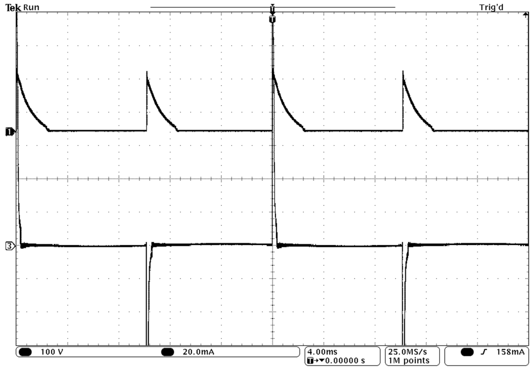
Output waveforms at half brightness setting (90° firing angle)



30126929

Ch1: Output Voltage (10 V/div); LED Current (100 mA/div); Time (4 ms/div)

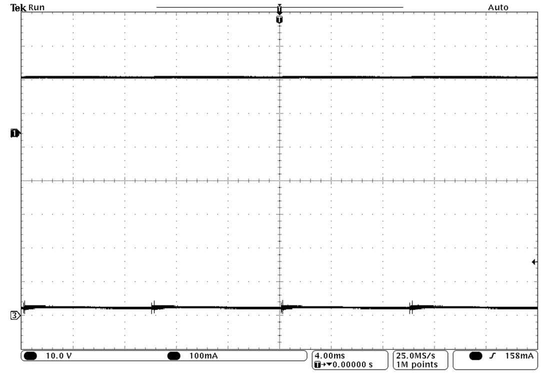
Input waveforms at minimum brightness setting



30126927

Ch1: Input Voltage (100 V/div); Ch3: Input Current (20 mA/div); Time (4 ms/div)

Output waveforms at minimum brightness setting

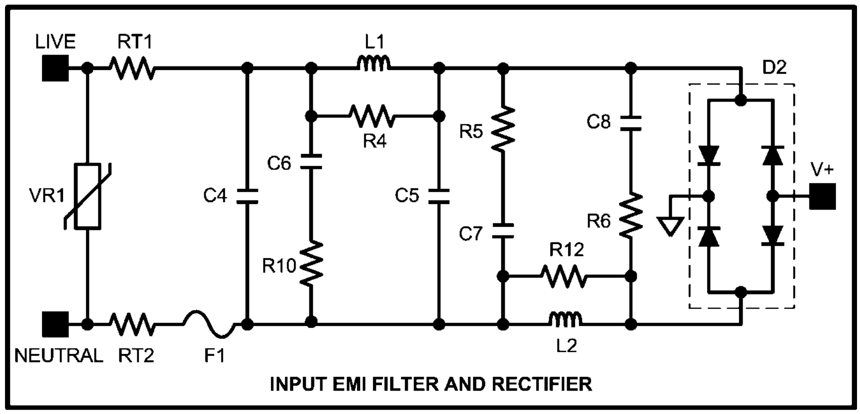


30126930

Ch1: Output Voltage (10 V/div); LED Current (100 mA/div); Time (4 ms/div)

Electromagnetic Interference (EMI)

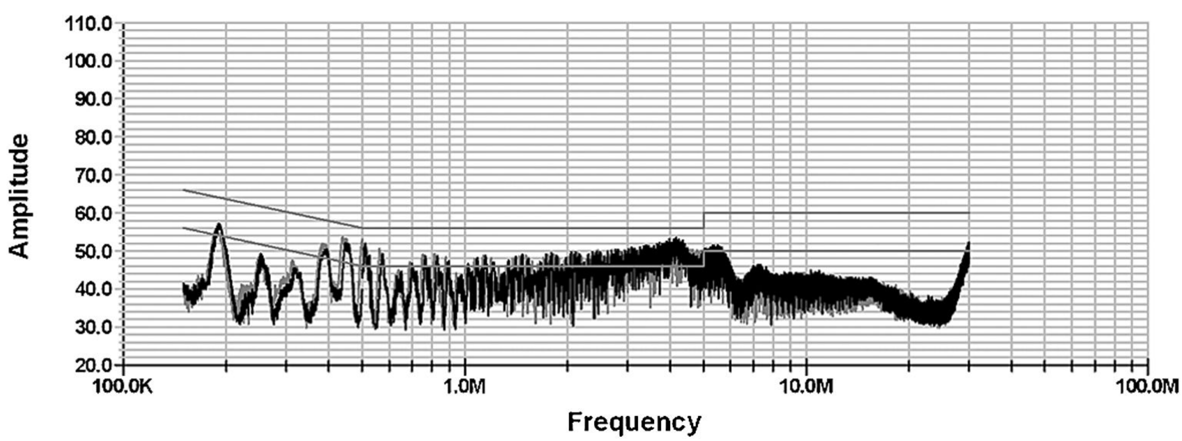
The EMI input filter of this evaluation board is configured as shown in the following circuit diagram.



30126931

FIGURE 1. Input EMI Filter and Rectifier Circuit

In order to get a quick estimate of the EMI filter performance, only the PEAK conductive EMI scan was measured and the data was compared to the Class B conducted EMI limits published in FCC – 47, section 15.(*Note 4*)



30126932

FIGURE 2. Peak Conductive EMI scan per CISPR-22, Class B Limits

Note 4: CISPR 15 compliance pending

Thermal Analysis

The board temperature was measured using an IR camera (HIS-3000, Wahl) while running under the following conditions:

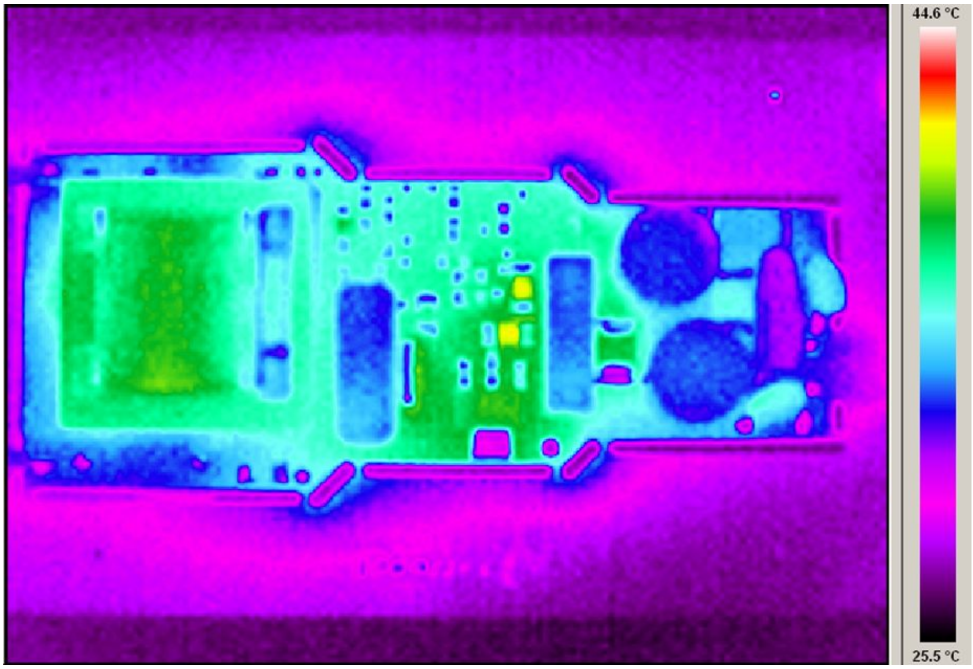
V_{IN} = 230 V_{RMS}

I_{LED} = 348 mA

\# of LEDs = 6

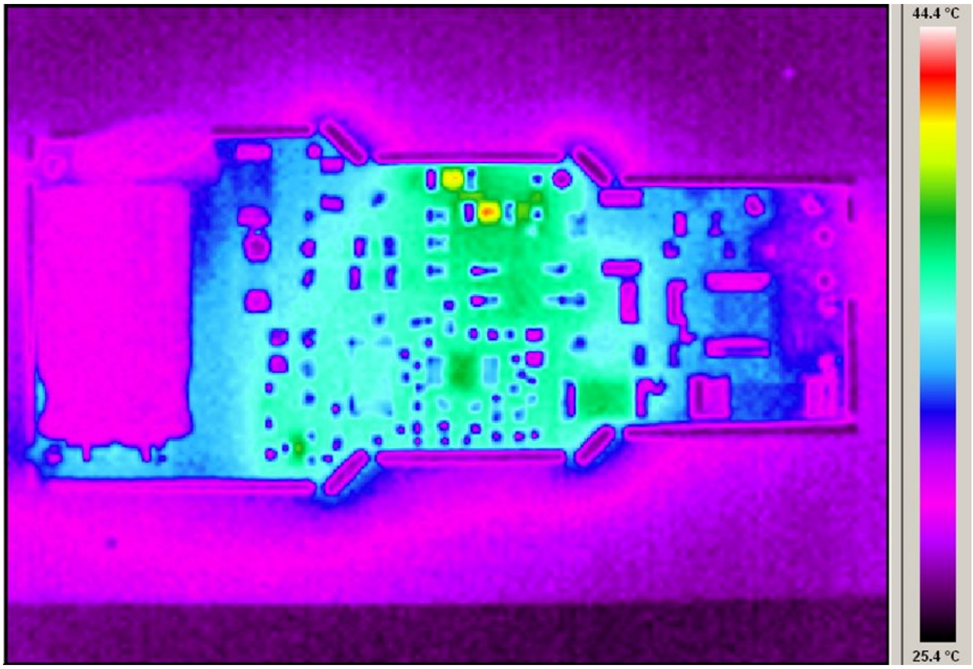
P_{OUT} = 7.2 W

The results are shown in the following figures.



30126933

FIGURE 3. Top Side Thermal Scan



30126934

FIGURE 4. Bottom Side Thermal Scan

Circuit Analysis and Explanations

INJECTING LINE VOLTAGE INTO FILTER-2 (ACHIEVING PFC > 0.94)

If a small portion (750mV to 1.00V) of line voltage is injected at FLTR2 of the LM3445, the circuit is essentially turned into a constant power flyback as shown in Figure 5.

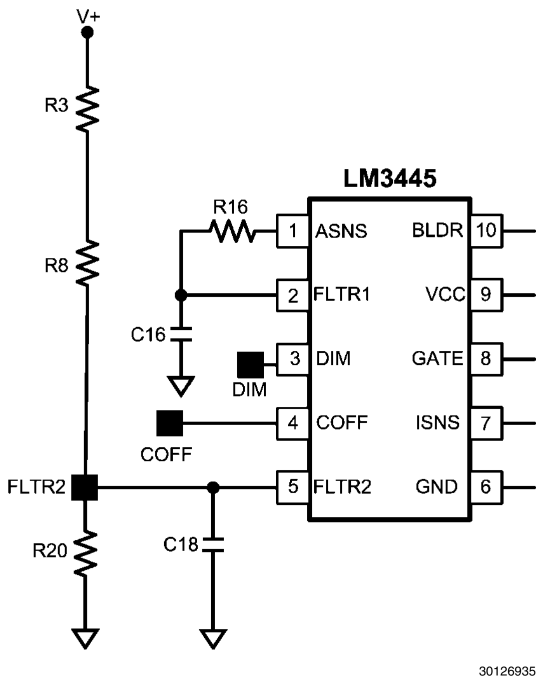


FIGURE 5. Line Voltage Injection Circuit

The LM3445 works as a constant off-time controller normally, but by injecting the $1.0V_{Pk}$ rectified AC voltage into the FLTR2 pin, the on-time can be made to be constant. With a DCM Flyback, Δi needs to increase as the input voltage line increases. Therefore a constant on-time (since inductor L is constant) can be obtained.

By using the line voltage injection technique, the FLTR2 pin has the voltage wave shape shown in Figure 6 on it with no triac dimmer in-line. Voltage at V_{FLTR2} peak should be kept below 1.25V. At 1.25V current limit is tripped. C11 is small enough not to distort the AC signal but adds a little filtering.

Although the on-time is probably never truly constant, it can be observed in Figure 7 how (by adding the rectified voltage) the on-time is adjusted.

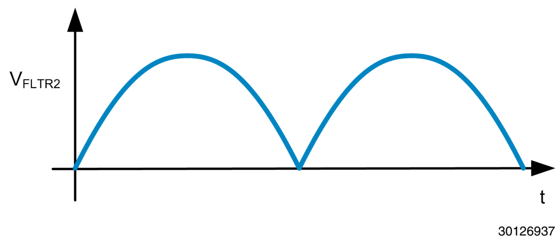


FIGURE 6. FLTR2 Waveform with No Dimmer

For this evaluation board, the following resistor values are used:

R3 = R8 = 309 kΩ

R20 = 1.91 kΩ

Therefore the voltages observed on the FLTR2 pin will be as follows for listed input voltages:

For VIN = $180V_{RMS}$, $V_{FLTR2, Pk}$ = 0.78V

For VIN = $230V_{RMS}$, $V_{FLTR2, Pk}$ = 1.00V

For VIN = $265V_{RMS}$, $V_{FLTR2, Pk}$ = 1.15V

Using this technique, a power factor greater than 0.94 can be achieved without additional passive active power factor control (PFC) circuitry.

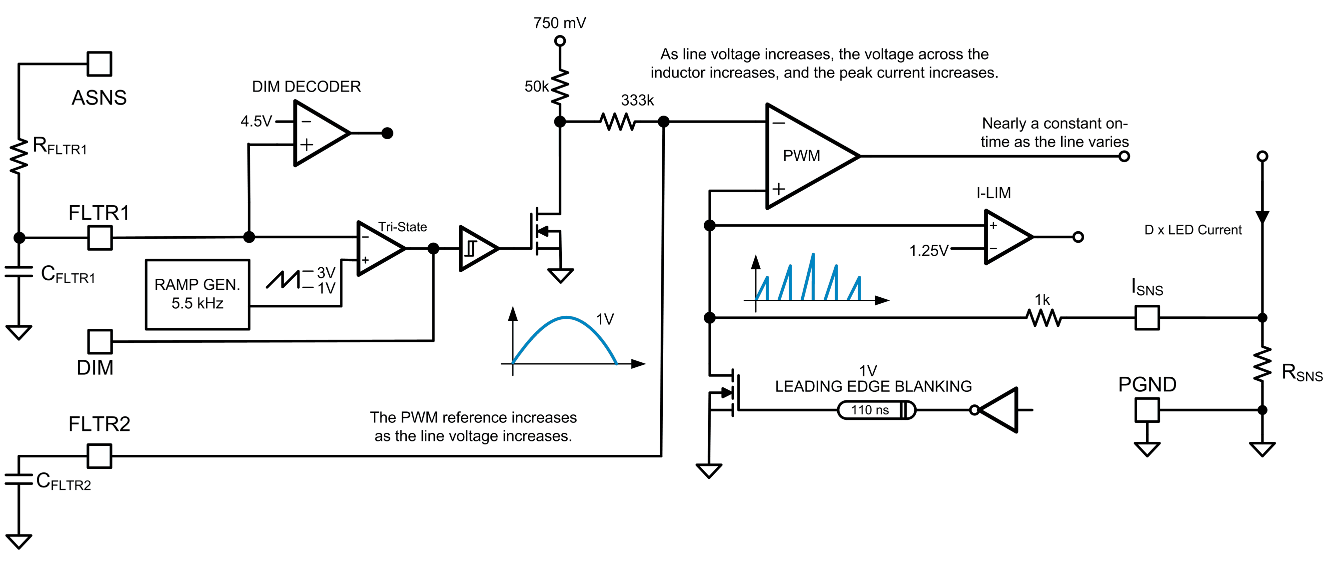


FIGURE 7. Typical Operation of FLTR2 Pin

Notes

Notes

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