19-W, Single-Stage AC/DC LED Driver for T8/T10 Fluorescent Lamp Replacement

Reference Design

TEXAS INSTRUMENTS

Literature Number: SLUU500
April 2011

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1 Introduction

This reference design, PMP4301, is a single-stage power factor corrected LED driver using Texas Instrument’s UCC28810 LED lighting power controller. The LED application focuses on fluorescent tube replacement lamp and wall-wash LED lighting with a small form factor, width less than 18 mm and height less than 11 mm, which can be inserted into tube 8 or tube 10 (T8/T10) designs directly. The driver can work with universal AC line input from 90 V_{RMS} to 265 V_{RMS} and provide a 450-mA constant current, at up to 42 VDC to drive a string with typically 12 LEDs in series.

2 Description

Based on the UCC28810 LED lighting power controller, this LED lighting driver reference design is capable of providing high power factor, output-load over-voltage protection, output-load short circuit protection, and open-loop protection, all with auto-recovery, along with long life, low profile, and low cost list of materials. The driver employs a single-stage PFC isolated flyback topology working in critical, or transition, mode. The power converter is designed to be used with T8/T10 isolated LED lamps with form factor and high efficiency. It can be packaged inside or outside the LED lighting housing.

2.1 Typical Applications

- T8/T10 Fluorescent Lamp Replacement
- Wall-Wash LED Lamp
- General LED Lighting

2.2 Features

- Universal Input Voltage Operation
- Single-Stage With Power Factor Correction
- Isolated Flyback Topology
- Constant Current Output for LED Lighting
- Integrated Protection for Output Short Circuit, Open Loop, and Output Over Voltage
- Low Height(<11 mm) With Form Factor for Fluorescent Lamp Replacement
- Critical Mode Operation With Valley Voltage Switching for High Efficiency

3 Electrical Performance Specifications

Table 1. PMP4301 Electrical Performance Specifications

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNITS
Input Characteristics					
Voltage range		90		265	V_{RMS}
Power Factor	V_{IN} = 230 V_{AC}, output current = 450 mA		0.956		
THD			13.5%		
Output Characteristics					
Output voltage, V_{OUT}	Output current = 450 mA	30	39	42	V
Output load current, I_{OUT}			450		mA
Output current ripple	V_{OUT} = 39 V, I_{OUT} = 450 mA, V_{IN} = 230 V_{AC}		106		mA_{PP}
Systems Characteristics					
Efficiency			87.7%		

4 Schematic

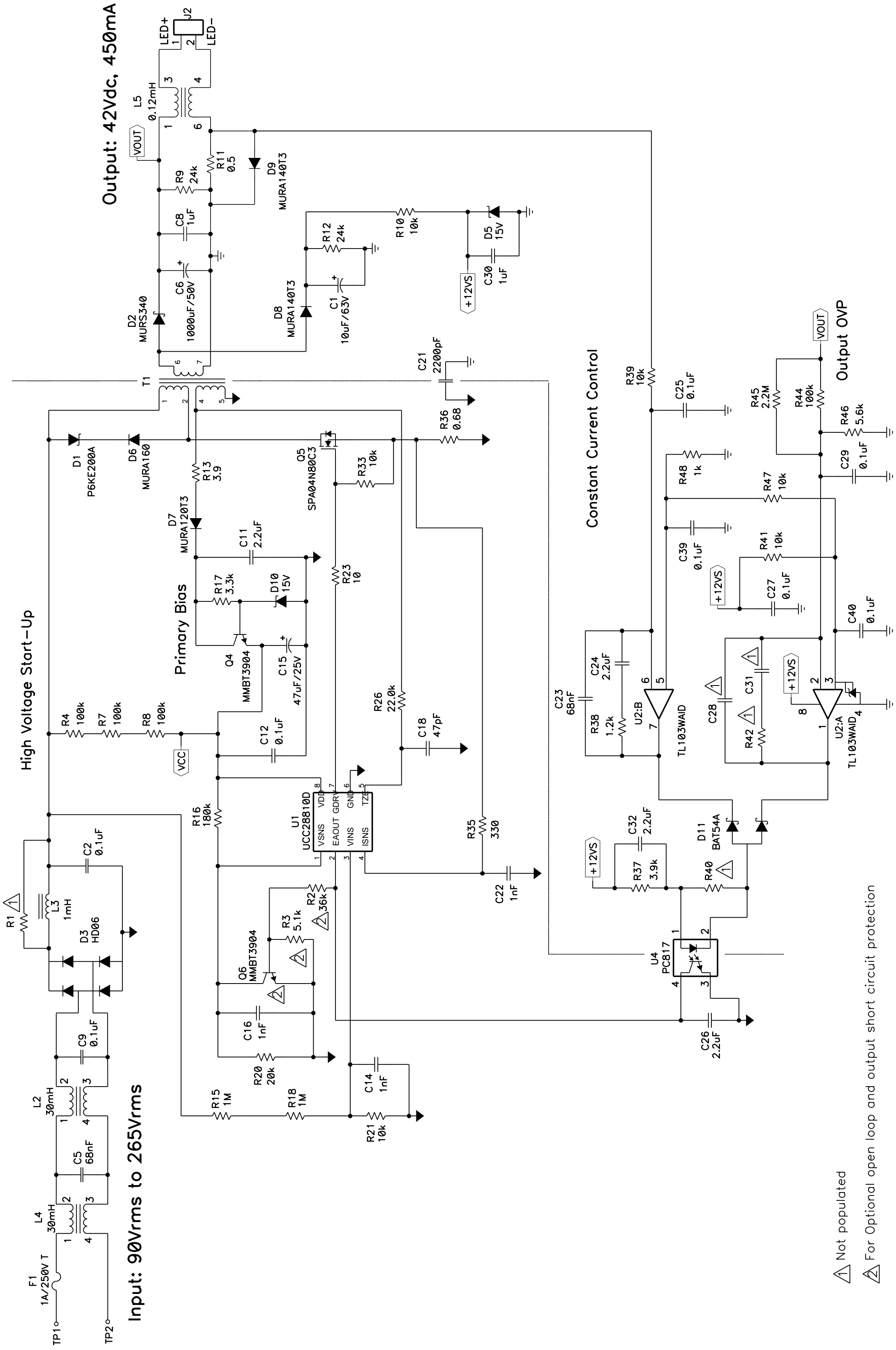


Figure 1. PMP4301 Reference Schematic

5 Theory of Operation

5.1 Single-Stage Flyback Converter With Power Factor Correction

This single-stage power factor corrected converter is an isolated flyback AC/DC topology that rectifies the AC input line to a DC output with an input sinusoidal current. The single-stage flyback topology is widely used as an isolated LED driver solution because it achieves high power factor with low component count, high reliability, and low cost without a large size 450-V_{DC} bulk capacitor. With constant-current sensing on the secondary output side, a single-stage flyback converter can operate with constant on-time and variable frequency modes to achieve a tightly regulated output current and high power factor for LED lighting applications.

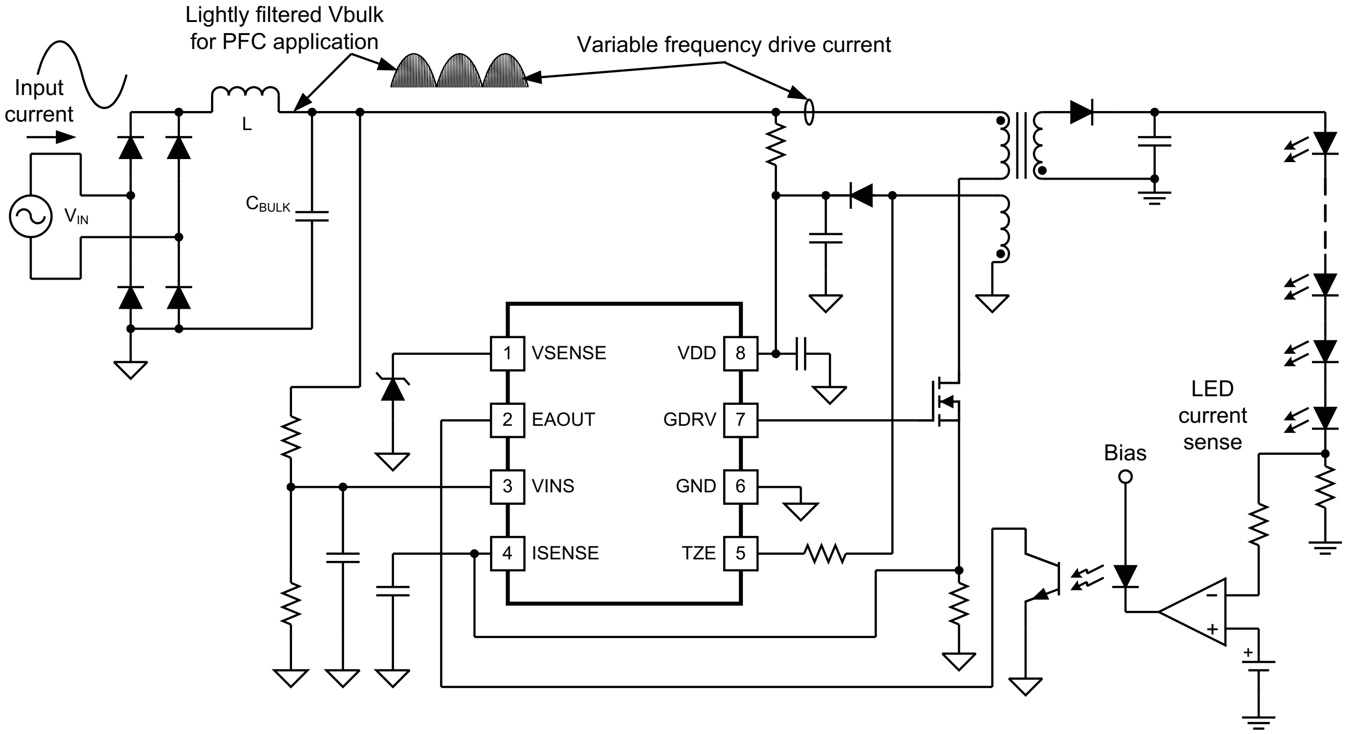


Figure 2. Input Current Tracks Input Voltage (Variable frequency control flyback using UCC28810)

As shown in Figure 2, the AC voltage, V_{IN}, is rectified by the input diode bridge which produces a half sine-wave voltage as the input voltage of the single-stage flyback PFC. A small capacitor, C_{BULK}, and a differential inductance, L, shown in Figure 2, are connected to the output of the diode bridge. C_{BULK} and L compose the differential mode low-pass filter. This filter can filter high-frequency switching ripple current and improve input power factor. The capacitor voltage should follow the AC input voltage. However, zero-crossing distortion of the half sine-wave voltage, V_{BULK}, is generated by C_{BULK}, resulting in decreased input power factor at high line. To avoid this, the capacitance value of C_{BULK} must be small. We need to determine C_{BULK} based on the input power factor and zero-crossing distortion. The UCC28810 as an LED lighting driver controller with high power factor can be programmed to operate at variable frequency control with input voltage sensing and transformer zero energy detection. In this way, the current of the primary side is working at critical conduction mode to get high power factor, and the switching frequency varies according to the input voltage feed forward and the output current feedback.

As mentioned above, the primary-side current of a single-stage flyback converter is operating at Critical Mode (CRM) with variable frequency control to achieve a sinusoidal input current with high PF. There is a common question: why can a single stage PFC operating in critical conduction mode achieve high power factor as opposed to other operating modes? To answer this question, the following calculations are shown. For critical mode control of each high frequency switching cycle:

$$V_{BULK} = L_p \times \frac{I_{PK}}{t_{ON}} \tag{1}$$

Where V_{BULK} is equal to the output voltage of the diode bridge,

- Lp is the primary-side inductance of the transformer,
- t_{ON} is the MOSFET on time,
- I_{PK} is equal to the peak current on the primary side.

For critical mode, the relationship between the average switching current and the peak current is given in Equation 2.

$$I_{AVG} = \frac{D \times I_{PK}}{2} \tag{2}$$

- I_{AVG} is the average current of the primary side, and
- D is the duty cycle for each switching operation.

Meanwhile:

$$V_{BULK} = \sqrt{2} V_{IN(rms)} \left| \sin \omega t \right| \tag{3}$$

$$P_{IN} = V_{IN(rms)} \times I_{IN(rms)} \times PF \tag{4}$$

Where P_{IN} is the input power which is equal to the output power divided by the converter efficiency,

- PF is equal to the Power Factor, and
- $V_{IN(rms)}$ and $I_{IN(rms)}$ are equal to the input RMS voltage and current, respectively.

In order for a single-stage flyback to operate at critical mode, the primary inductance of the transformer is a very important parameter. The formula to calculate the primary inductance of the transformer for critical mode single-stage operation is shown in Equation 4.

$$L_p = \frac{{V_{IN(rms)}}^2}{2 \times P_{IN} \times f_{SW}} \times D^2 \times PF = \frac{1}{2 f_{SW} P_{IN}} \times \left(\frac{n V_O V_{IN(rms)}}{\sqrt{2} V_{IN(rms)} + n V_O} \right)^2 \times PF \tag{5}$$

In Equation 4, refer to the transformer turns ratio, Np/Ns,

- f_{SW} is the switching frequency,
- n is the transformer turns ratio,
- $V_{IN(rms)}$ is the input RMS voltage, and
- V_O is the output voltage.

Also, the output voltage of the diode bridge, V_{BULK}, can be determined by Equation 6.

$$V_{BULK} = \sqrt{2}V_{IN(rms)} \times |\sin \omega t| = L_p \times \frac{I_{PK}}{D} \times f_{SW} = \frac{I_{AVG} \times V_{IN(rms)}^2}{P_{IN}} \times PF \tag{6}$$

In the theory analysis, there is an assumption that the instantaneous input current is approximately equal to average current of each high-frequency switching cycle. From Equation 1 to Equation 6, we can derive:

$$|i_{IN}| \approx I_{AVG} = \frac{\sqrt{2}P_{IN}}{V_{IN} \times PF} \times |\sin \omega t| \tag{7}$$

According to Equation 7, the absolute value of the instantaneous input current is equal to the average primary inductor current, and the input current is ideally following a sine wave as input power and input voltage is determined. Therefore, we can conclude that the single stage with critical mode has high power factor correction.

Because the T8 fluorescent lighting form factor is very limited, the transformer should be designed to be ultra slim and have low height in order to insert the LED driver into the tube lighting's vessel. In this reference design, PMP4301, a dedicated core and bobbin is used to build the transformer with a width of less than 13 mm and height less than 11 mm. The design has balanced the transformer's core loss and copper loss in order to achieve the highest efficiency for this 19-W single-stage flyback LED driver.

5.2 UCC28810 Controller

The UCC28810 is generally used for converters for lighting applications from low-to-medium power lumens requiring PFC and EMC compliance. It can be used for controlling a flyback, buck, or boost converter operating in critical conduction mode to acquire high PF. It features a transconductance voltage amplifier for feedback error processing, a simple current reference generator for generating a current command proportional to the input voltage, a current-sense (PWM) comparator, PWM logic, and a totem-pole driver for driving an external FET. In critical conduction mode operation, the PWM circuit is self-oscillating with the turn-on of the primary-side switch being governed by the detection of the transformer zero energy at the TZE pin and the turn-off of the switch being governed by the current-sense comparator. Additionally, the controller provides features such as peak current limit, restart timer, Overvoltage Protection (OVP), and enable control.

As shown in Figure 3, during start up, V_{BULK} will charge C15 through R4, R7, and R8 which will increase the VDD voltage of UCC28810 up to the turn-on threshold and the converter will operate with several switching cycles. During normal operation, the auxiliary winding of transformer will power up the controller's VDD through D7, C11, Q4, and C15. The UCC28810 has enough drive capability to drive the power MOSFET Q5 directly with variable switching frequency operation.

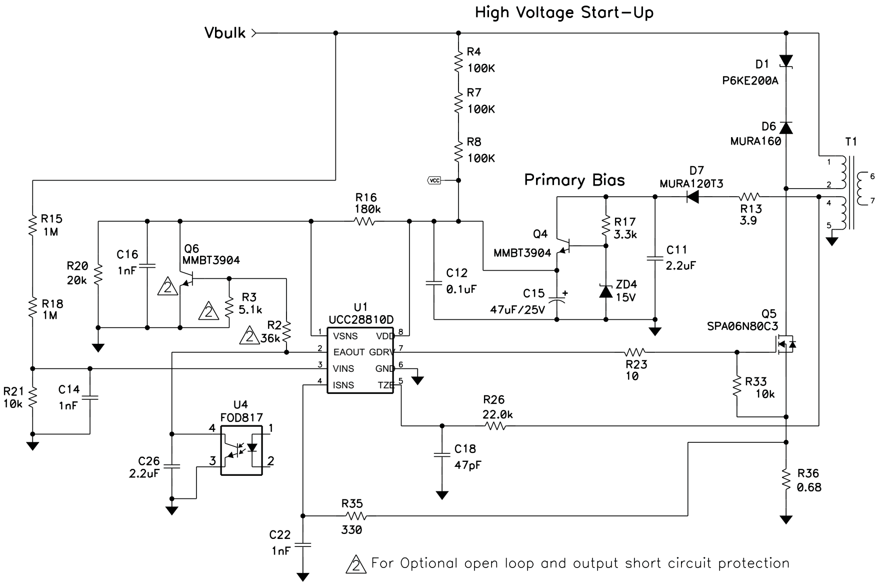


Figure 3. UCC28810 Control Chip, Start Up, Drive Circuit for PMP4301

A zero-crossing signal from the auxiliary winding is filtered by R26 and C18. This voltage signal is delivered to the TZE pin to detect the demagnetization of the transformer which is required before the controller can switch on the power MOSFET, Q5, with a gate drive turn-on trigger signal. The instantaneous half sine-wave input voltage is sensed by R15, R18, R21, and C14 and this input voltage feed forward signal is transferred to pin 3, VINS, of the UCC28810 controller. This input voltage feed forward signal and the output constant current feedback signal on EAOUT are used as the reference signal for the current control loop. Their product is compared with the current sensing signal of the MOSFET, Q5 as detected at pin 4, ISNS, and this determines when Q5 is turned off. The current sensing signal of MOSFET Q5 is achieved and filtered by R36, R35 and C22. In this way MOSFET Q5 turn on and turn off is controlled to achieve low input current distortion and high power factor.

R2, R3, and Q6 provide an optional open-loop or output short circuit protection function. When any open loop or output short circuit event happens , Q6 will pull the VSNS pin low and protect the power stage from damage, and the output switching will be turned off.

5.3 Secondary-Side Current Feedback

The secondary circuit for this LED driver is shown in Figure 4. This LED driver is a conventional flyback configuration consisting of free-wheel diode D2 and output filter capacitors C6 and C8. The control circuit is a constant current loop.

The output LED current is sensed by resistor R11. Diode D9, in parallel with R11, will protect R11 from damage by the inrush current if the output is shorted. This current feedback signal is filtered by R39 and C25, then the filtered feedback signal is compared to a reference signal formed by R47 and R48, and the error signal is integrated by U2 TL103. This generates the control signal for the constant current loop. This control signal sets the opto-coupler U4 sinking current. In this way the control voltage for the constant current loop is delivered to the primary side control circuit in order to regulate the switching frequency resulting in constant output current.

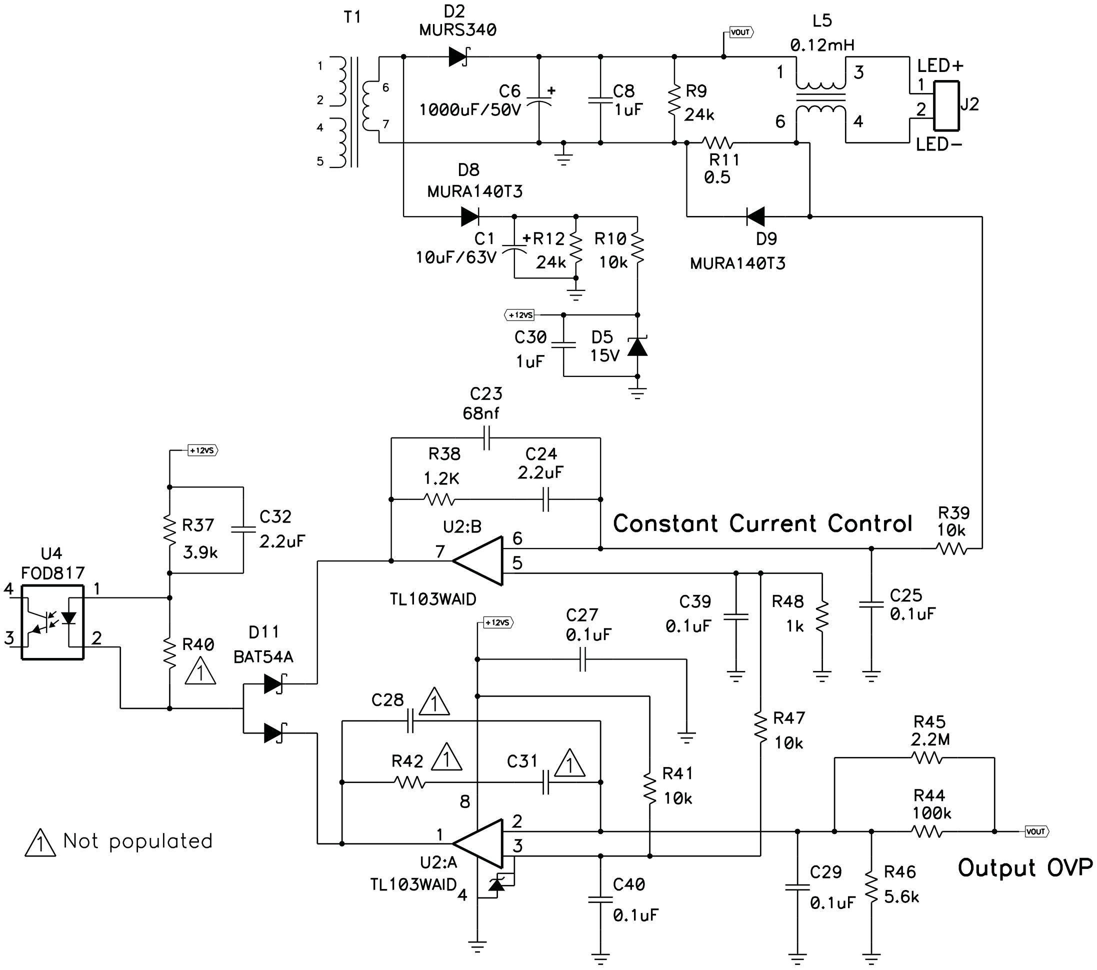


Figure 4. Secondary-Side Load Current Channel

6 PCB Layout

This reference design has been implemented on a double-sided PCB that is dimensionally compatible with T8/T10 fluorescent lamps and similar applications. It has been made physically small to show the practicality of a single-stage PF correcting converter using a UCC28810 control device. Its dimensions measured 245 mm long by 18 mm wide by 11 mm high.

6.1 Top Side of PMP4301 Layout

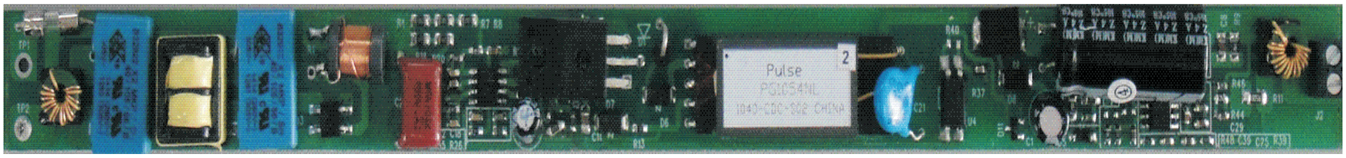


Figure 5.

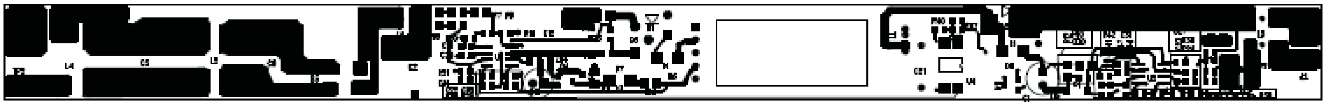


Figure 6.

6.2 Bottom side of PMP4301 PCB Layout

Figure 7.

7 Performance Data and Typical Characteristic Curves

Section 7.1 to Section 7.4 present typical performance curves for the 42-V, 450-mA, PMP4301T8/T10 LED driver.

7.1 Power Factor (PF)

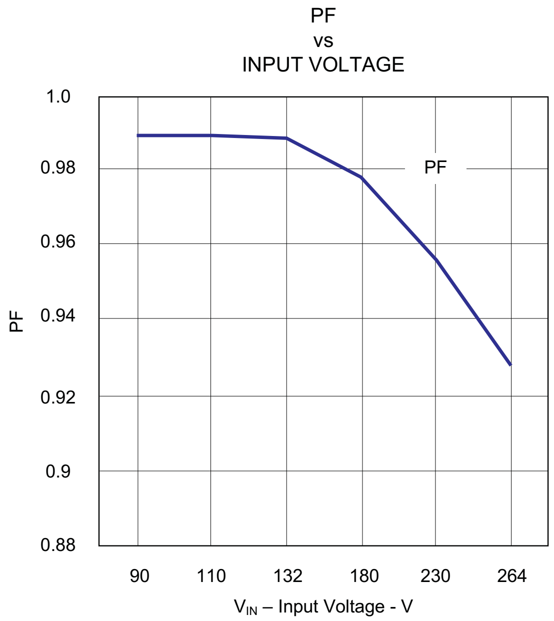


Figure 8.

7.2 Total Harmonic Distortion (THD)

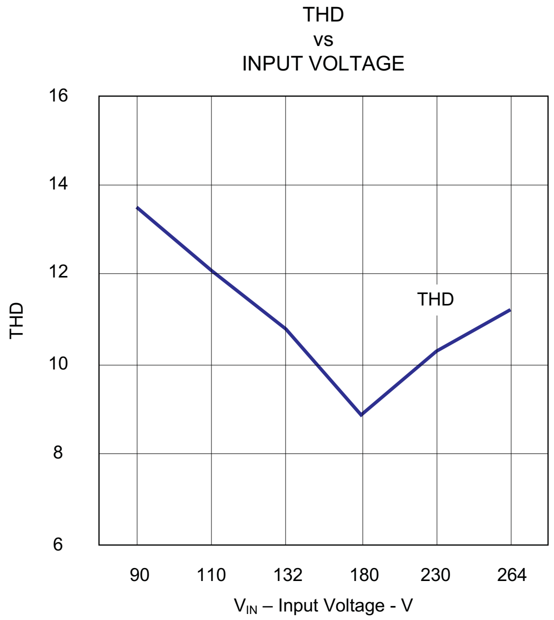


Figure 9.

7.3 Output Current

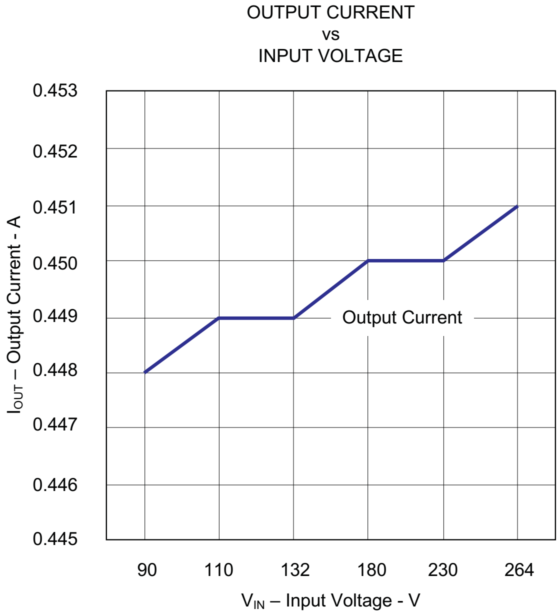


Figure 10.

7.4 Efficiency

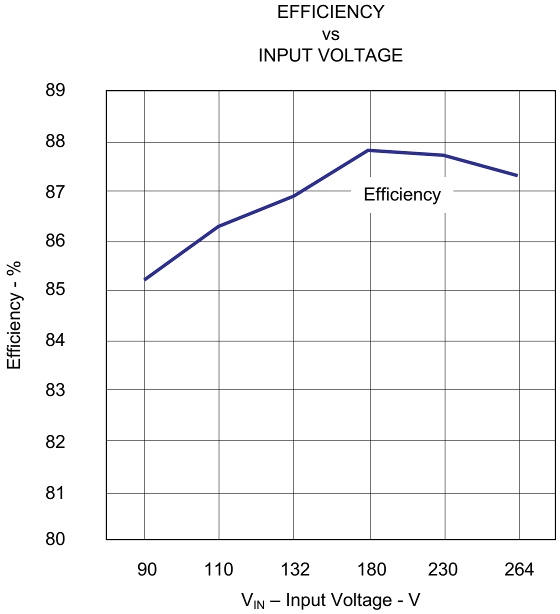


Figure 11.

8 Electrical Performance

8.1 Input voltage and current

Channel 2: input voltage 200 V/div.

Channel 4: input current 200 mA/div.

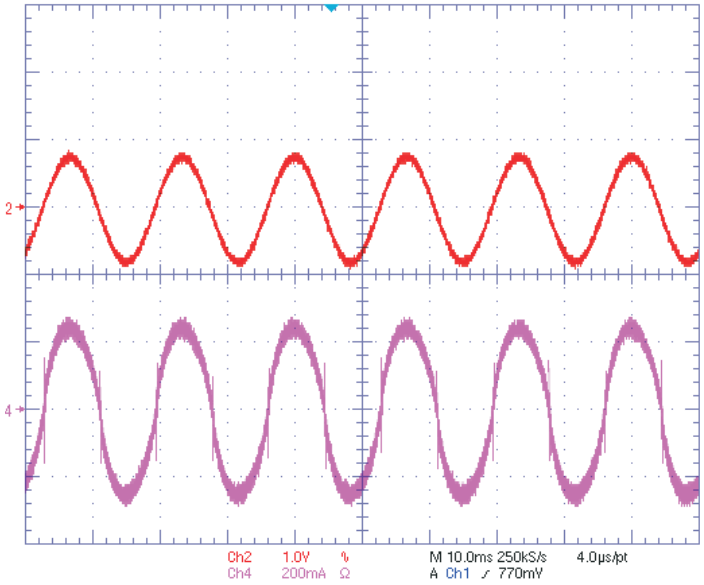


Figure 12. Input Current With 110-VAC Input Voltage and Full Load

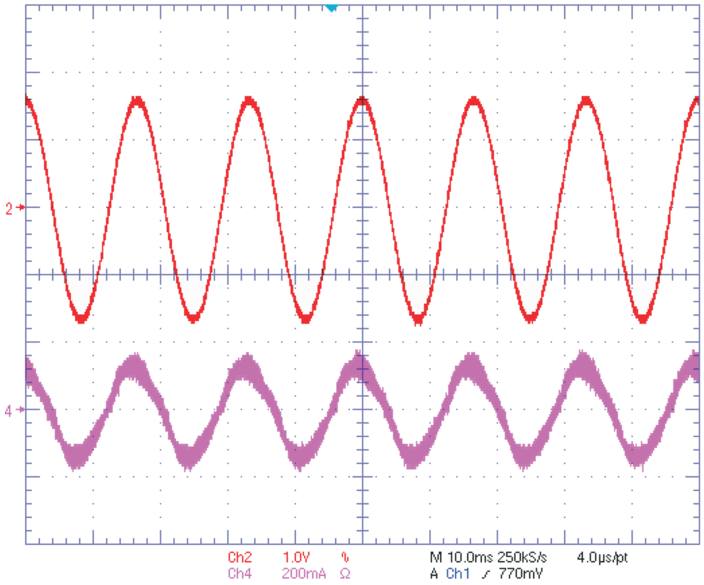


Figure 13. Input Current With 230-VAC Input Voltage and Full Load

8.2 Turn-On Delay

Channel 1: output voltage 20 V/div.

Channel 2: input voltage 100 V/div.

Channel 4: output current 200 mA/div.

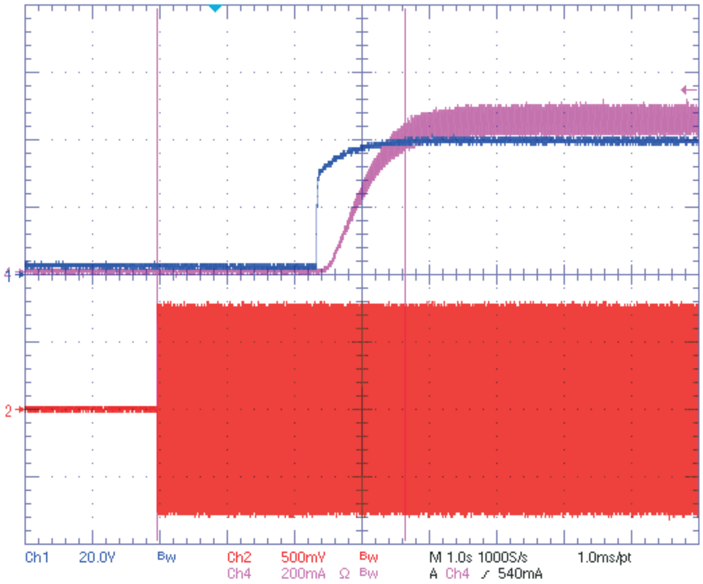


Figure 14. Turn-On Delay With 110-VAC Input Voltage and Full Load

Channel 1: output voltage 20 V/div.

Channel 2: input voltage 200 V/div.

Channel 4: output current 200 mA/div.

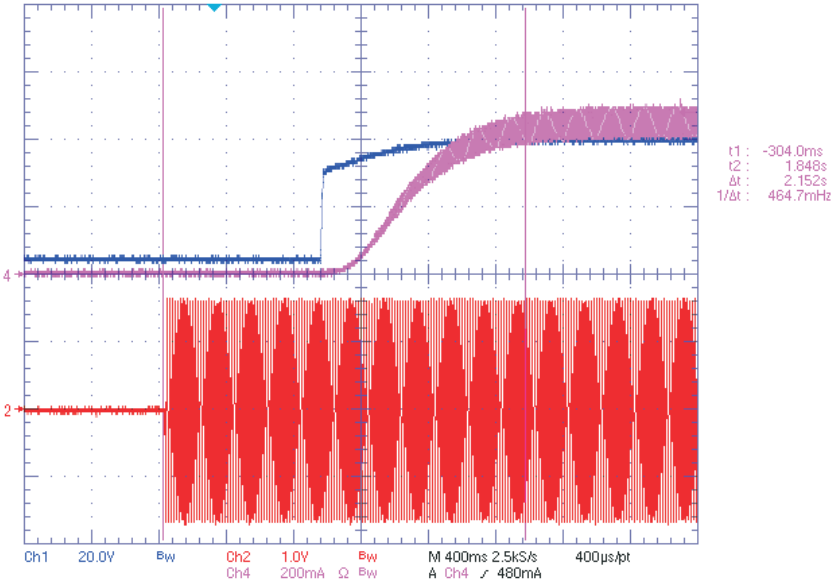


Figure 15. Turn-On Delay With 230-VAC Input Voltage and Full Load

8.3 Output Ripple Current

Channel 1: output voltage 20 V/div.

Channel 2: input voltage 200 V/div.

Channel 4: output current 50 mA/div.

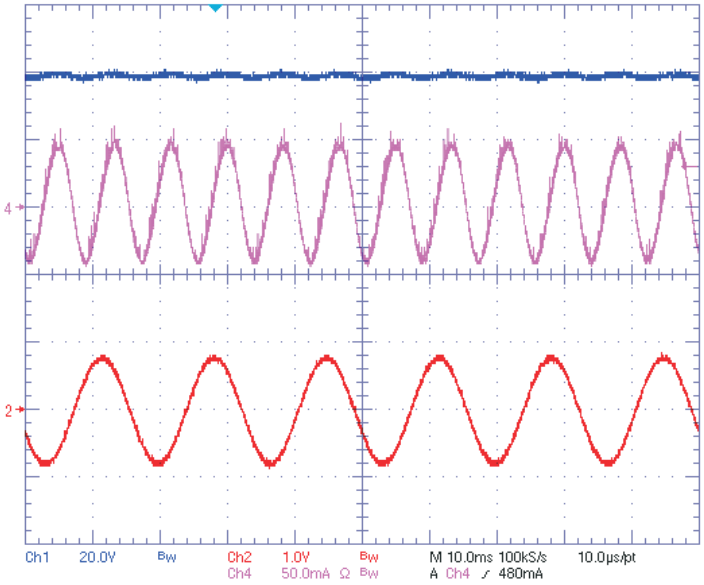


Figure 16. Output Ripple Current With 110-VAC Input Voltage and Full Load

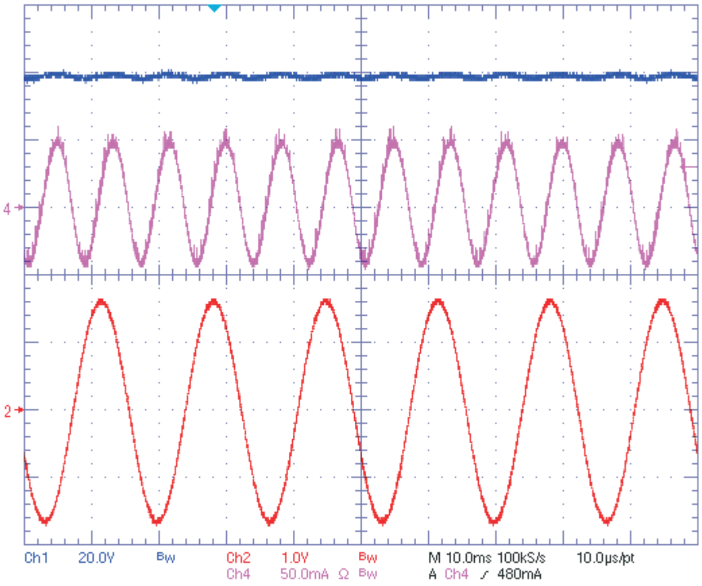


Figure 17. Output Ripple Current With 230-VAC Input Voltage and Full Load

8.4 Output Over Voltage Protection

Channel 1: output voltage 10 V/div.

Channel 4: output current 200 mA/div.

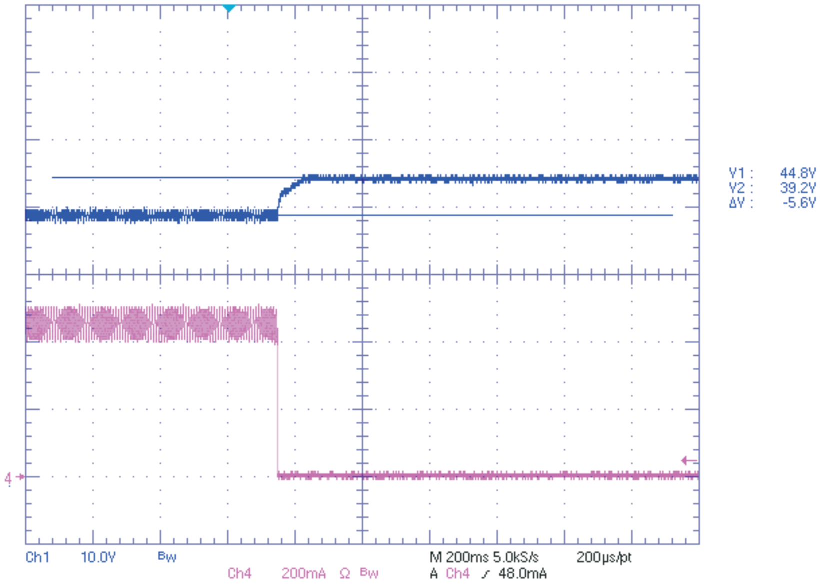
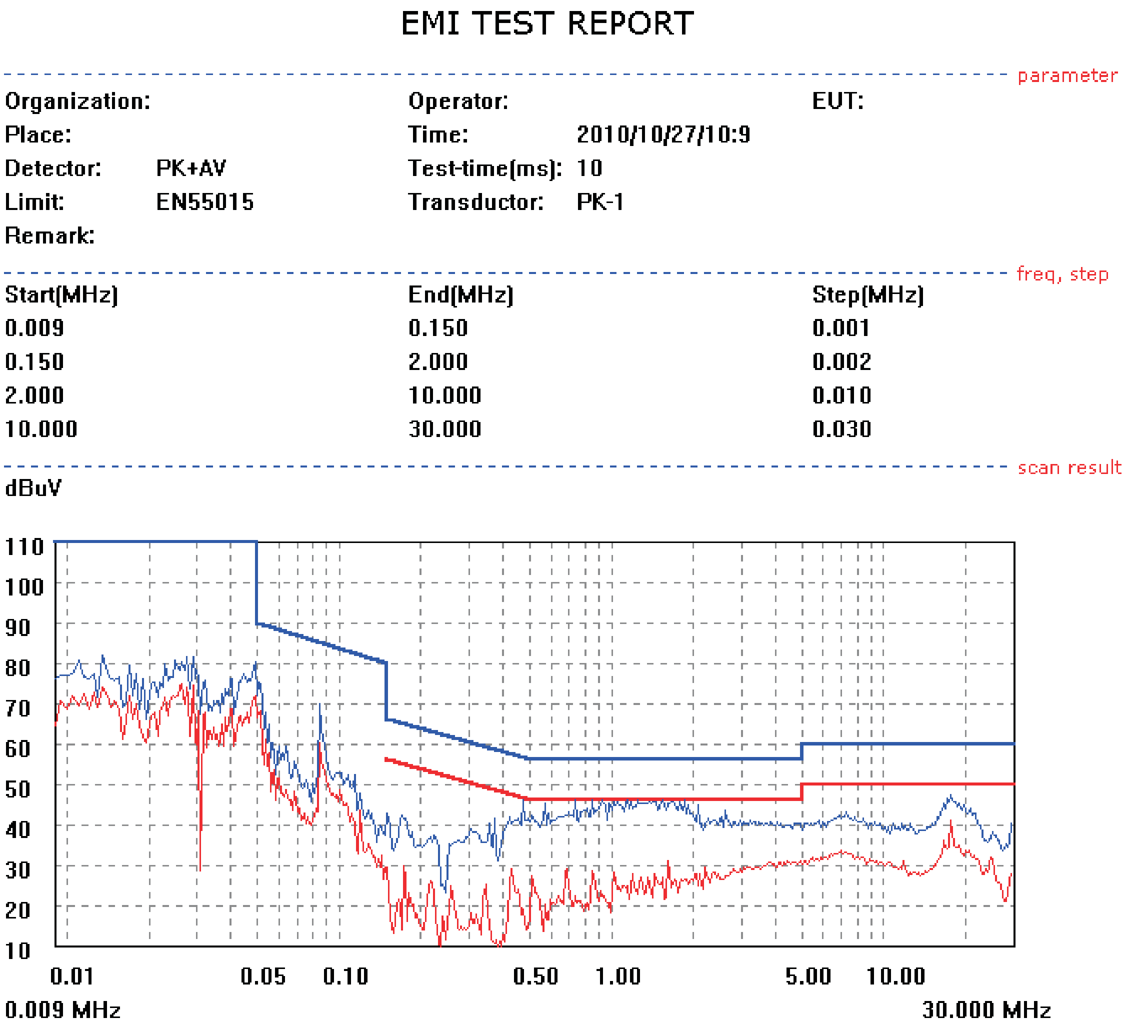


Figure 18. Output Over Voltage With 230-VAC Input Voltage From Full Load to Open Circuit

9 Conducted EMI



EMI TEST REPORT

parameter

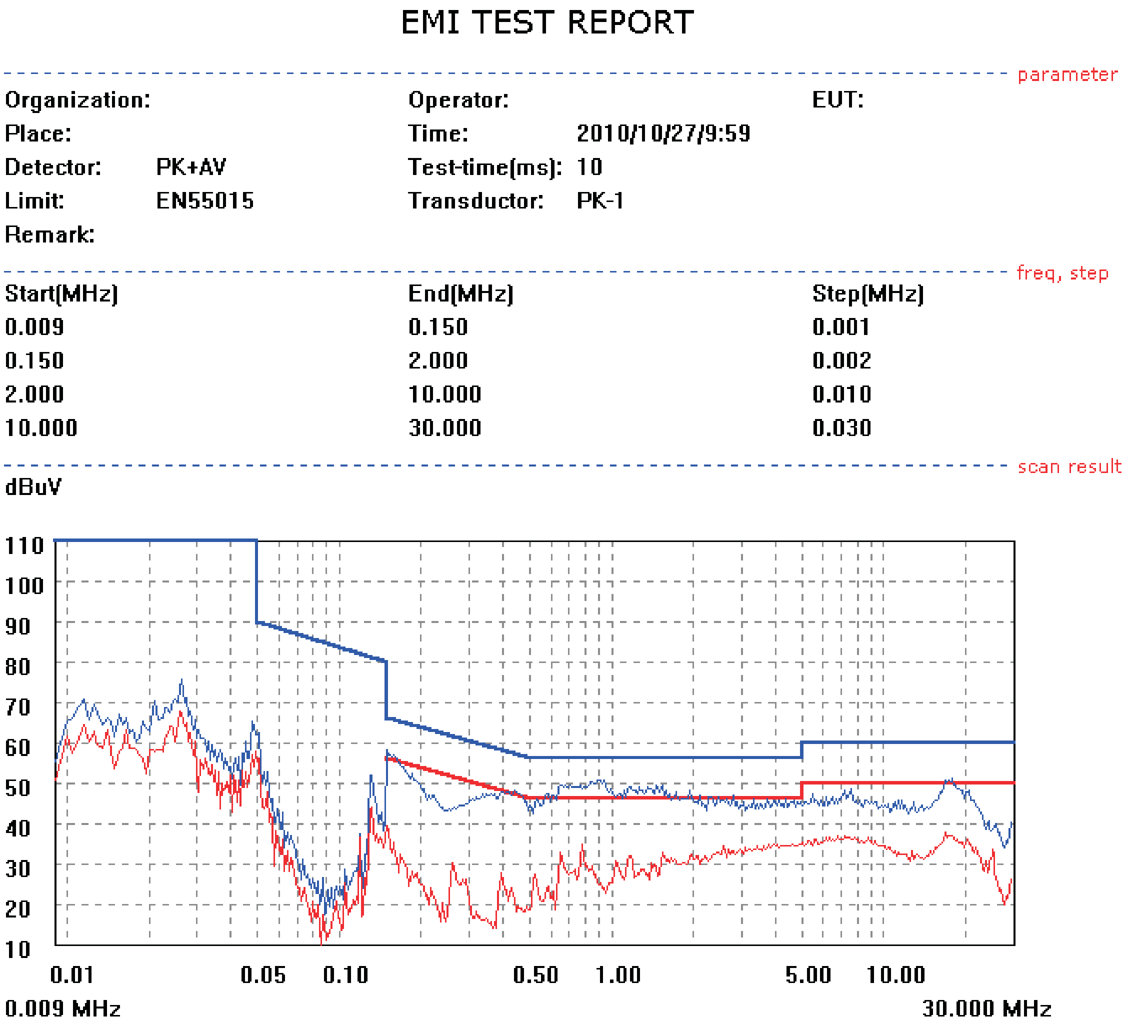
Organization:		Operator:		EUT:
Place:		Time:	2010/10/27/10:9	
Detector:	PK+AV	Test-time(ms):	10	
Limit:	EN55015	Transducer:	PK-1	
Remark:				

freq, step

Start(MHz)	End(MHz)	Step(MHz)
0.009	0.150	0.001
0.150	2.000	0.002
2.000	10.000	0.010
10.000	30.000	0.030

scan result

Figure 19. Conducted EMI With 110-VAC Input Voltage With 12 LEDs at Full Load



EMI TEST REPORT

parameter

Organization:		Operator:		EUT:
Place:		Time:	2010/10/27/9:59	
Detector:	PK+AV	Test-time(ms):	10	
Limit:	EN55015	Transducor:	PK-1	
Remark:				

freq, step

Start(MHz)	End(MHz)	Step(MHz)
0.009	0.150	0.001
0.150	2.000	0.002
2.000	10.000	0.010
10.000	30.000	0.030

scan result

Figure 20. Conducted EMI With 230-VAC Input Voltage With 12 LEDs at Full Load

10 List of Materials

Table 2. PMP4301 Component List of Materials

QTY	REF DES	DESCRIPTION	MFR	PART NUMBER
1	C1	Capacitor, 10 µF, 50 V, +/-20%	Samxon	EKS106M1HE07RR
1	C2	Capacitor, 0.1 µF, 450 V, film box type 10%	Panasonic	ECWF2W104KAQ
1	C5	Capacitor, AP, 68 nF, 305 VAC, EMI suppressn	EPCOS	B32921C3683M
1	C9	Capacitor, 0.1 µF, 305 VAC, EMI suppressn	EPCOS	B32921C3104M
1	C6	Capacitor, 1000 µF, 50 V, +/-20%	Samxon	EKM108M1HG20RR
1	C8	Capacitor, ceramic, 1 µF, 50 V, X7R, 20%	muRata	ECJ2FF1H105Z
1	C11	Capacitor, ceramic, 2.2 µF, 25 V, X7R, 0805	muRata	GCM21BR71E225KA73
6	C12,C25, C27, C29,C39, C40	Capacitor, ceramic, 0.1 µF, 25 V, X7R, RAD	muRata	RDER71E104K0K1C03B
3	C14,C16, C22	Capacitor, ceramic, 1nF, 16 V, 10%, X7R, 0603	muRata	GRM033R71C102KD01D
1	C15	Capacitor, aluminum, 25 V, 47 µF, 20%	Samxon	EKS476M1CD07RR
1	C18	Capacitor, ceramic, 47 pF, 25 V, 5%, C0G, 0603	muRata	GRM0335C1E470JD01D
1	C21	Capacitor, ceramic, 2200 pF, 250 VAC, Y1	Panasonic	ECKANA222MB
1	C23	Capacitor, ceramic, 68 nF, 16 V, 10%, X7R, 0603	muRata	GRM188R71C683KA01D
3	C24,C26, C32	Capacitor, ceramic, 2.2 µF, 16 V, X5R, 0603	muRata	GRM188R61C225KE15D
1	C30	Capacitor, ceramic, 1 µF, 16 V, X7R, 0603	muRata	GRM188R71C105KA12D
1	D1	DIODE, transient voltage suppressor, 200 V	Vishay	P6KE200A
1	D2	Diode, Schottky, 3 A, 400 V	ON Semi	MURS340T3G
1	D3	Bridge rectifier, 600 V, 0.8 A	Diodes	HD06
2	D5,ZD4	Diode, Zener, 15 V, 5 mA	Diodes	BZT52C15
1	D6	Ultrafast rectifier, 1 A, 600 V	ON Semi	MURA160T3
1	D7	Diode, ultra fast rectifier, 1 A, 200 V	ON Semi	MURA120T3
2	D8,D9	Diode, ultra fast rectifier, 1 A, 400 V	ON Semi	MURA140T3
1	D11	Diode, dual Schottky, 300 mA, 40 V	ST	BAT54AFILM
1	F1	Fuse, 1 A, 250 VAC	std	1A/250Vac
1	J2	Terminal block, 2 pin, 6 A, 3.5 mm	OST	ED555/2DS
1	L3	I-inductor, DR8-10, 1 mH	HHA	DR8-10
2	L2,L4	Common choke, EI-11.6, 30 mH	HHA	EI-11.6
1	L5	Common choke, T6-3-2, 0.12 mH	HHA	T6-3-2
1	Q4	Bipolar, NPN, 40 V, 200 mA, 330 mW	Infineon	MMBT3904LT1
1	Q5	MOSFET, N-channel, 800 V, 1.3 Ω	Infineon	SPA04N80C3

Table 2. PMP4301 Component List of Materials (continued)

QTY	REF DES	DESCRIPTION	MFR	PART NUMBER
3	R4,R7,R8	Resistor, chip, 1/10 W, 100 kΩ, 1%, 0805	std	std
2	R9,R12	Resistor, chip, 1/10 W, 24 kΩ, 1%, 0805	std	std
1	R10	Resistor, chip, 1/10 W, 10 kΩ, 1%, 0805	std	Std
1	R11	Resistor, chip, 1/4 W, 0.5 Ω, 5%, 1206	Std	Std
1	R13	Resistor, chip, 1/16 W, 3.9 Ω, 1%, 0603	Std	Std
2	R15,R18	Resistor, chip, 1/10 W, 1 MΩ, 1%, 0805	std	std
1	R16	Resistor, chip, 1/16 W, 180 kΩ, 1%, 0603	Std	Std
1	R17	Resistor, chip, 1/16 W, 3.3 kΩ, 1%, 0603	Std	Std
1	R20	Resistor, chip, 1/16 W, 20 kΩ, 1%, 0603	Std	Std
5	R21,R33, R39, R41,R47	Resistor, Chip, 1/16 W, 10 kΩ, 1%, 0603	Std	Std
1	R23	Resistor, chip, 1/16 W, 10 Ω, 1%, 0603	Std	Std
1	R26	Resistor, chip, 1/16 W, 22 kΩ, 1%, 0603	Std	Std
1	R35	Resistor, chip, 1/16 W, 330 Ω, 1%, 0603	Std	Std
1	R36	Resistor, chip, 1/4 W, 0.68 Ω, 5%, 1206	Std	Std
1	R37	Resistor, chip, 1/16 W, 3.9 kΩ, 1%, 0603	Std	Std
1	R38	Resistor, chip, 1/16 W, 1.2 kΩ, 1%, 0603	Std	Std
1	R44	Resistor, chip, 1/16 W, 100 kΩ, 1%, 0603	Std	Std
1	R45	Resistor, chip, 1/16 W, 2.2 MΩ, 1%, 0603	std	std
1	R46	Resistor, chip, 1/16 W, 5.6 kΩ, 1%, 0603	Std	Std
1	R48	Resistor, chip, 1/16 W, 1 kΩ, 1%, 0603	Std	Std
1	T1	Transformer, Lp = 520 µH	Pulse	PG1054NL-S04
1	U1	LED Lighting Power Controller	TI	UCC28810D
1	U2	Dual OPAMP With Internal Reference	TI	TL103WAID
1	U4	Optocoupler, 35 V, 600% CTR	SHARP	PC817CIJ000F

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