ON Semiconductor

Design Note – DN06050/D

7 W, 90-135 Vac, 500 mA LED Driver

Device	Application	Input Voltage	Output Power	Topology	I/O Isolation
NCP1216 MUR240	LED Driver	90-135 Vac	7 Watts	Buck	no

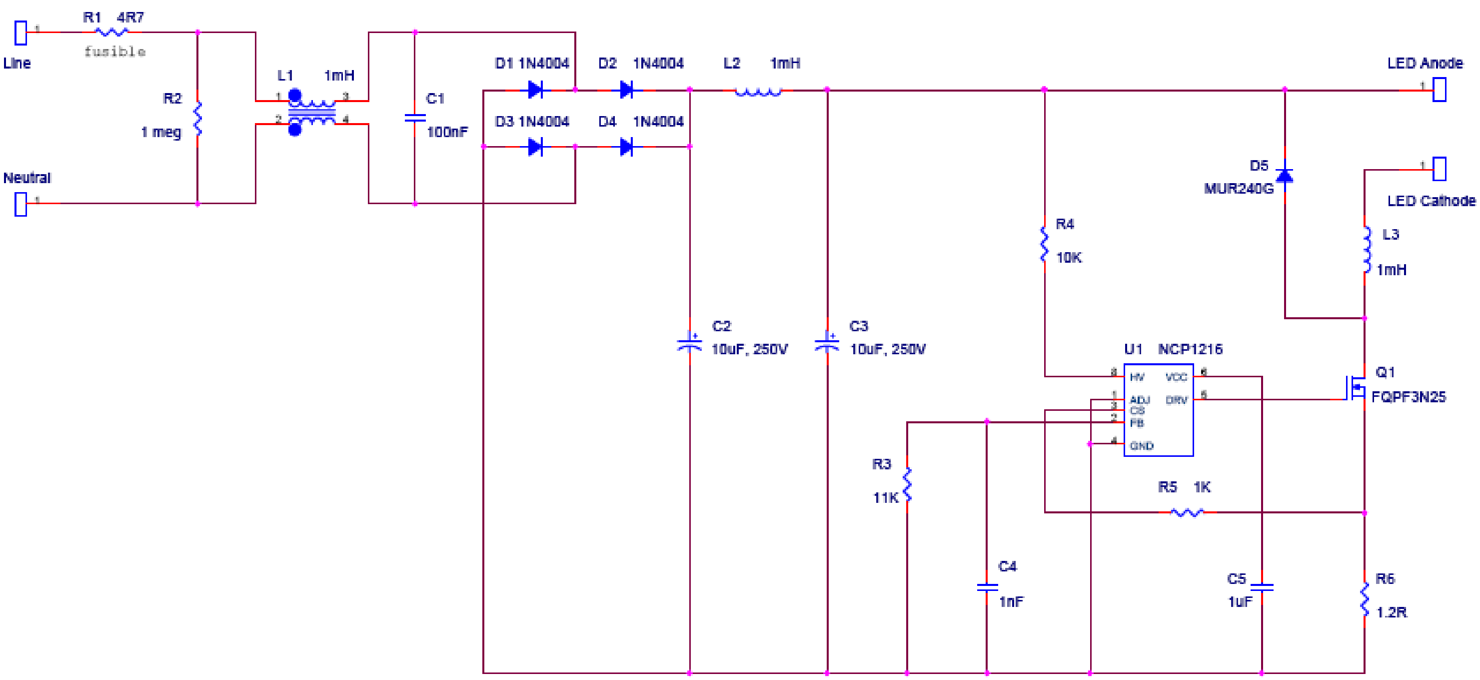


Figure 1: Basic schematic

Circuit Description

This non-isolated constant current buck LED driver design has been optimized to drive 4 high power high current LEDs such as the Cree XLAMP™ XR-E/XP-E, Luxeon™ Rebel, Seoul Semiconductor Z-Power, or OSRAM Golden Dragon™. Design requirements include long life operation targeting cost sensitive general lighting applications and typical efficiency of 80% at maximum load. While the design example used is targeted at 4 White LEDs with a forward voltage range of 12-16 Vdc at 500 mA, other current and forward voltage range options can be accommodated through component changes to the BOM.

Long life operation is ensured by controlling stress ratio and minimizing the number of parts. A solution based on the NCP1216 current mode controller provides design flexibility for optimization with few external parts. The external FET switch can be selected to balance performance and cost considerations. While integrated high voltage switching regulator solutions are available, these devices are based on power switches rated at 650 volts or more which is much higher than required in this application. Moreover separating the power switch allows better thermal management while optimizing the external power switch to provide better performance as the voltage rating and $R_{DS(on)}$ can be optimized for the application needs.

Theory of Operation

A buck regulator operating well into continuous current conduction provides a solution which does not require output storage capacitors. The buck inductor current is the same as the LED current consisting of a constant current with a superimposed AC component. While a discontinuous or critical conduction solution could be considered, filter capacitors on the output would be required. This adds to cost, size and impacts system reliability.

Several factors are balanced to optimize this design. A 65 kHz switching frequency was chosen allowing the EMI filter to effectively attenuate harmonics below where the conducted emissions requirement begins at 150 kHz.

Continuous mode operation requires the output rectifier to switch off while conducting full current. Reverse recovery time is therefore critical in maintaining high efficiency as the power switch must carry inductor current plus rectifier recovery current for the duration of recovery time each switching cycle. Selecting a fast rectifier with low reverse recovery time and operating at the lower switching frequencies minimizes switching losses.

Duty factor or on-time of the power switch follows the equation D = (Vout/Vin). Vin is the peak rectified bulk voltage which for 115 Vac input is 162 Vdc. Four LEDs at 3.5 Vdc nominal forward voltage equal a Vout of 14 Vdc. The duty factor is then D = (14/162) = 0.086. This relatively low duty factor means the FET power switch is On only a small percentage of the time and therefore conduction losses are less of a concern. The power FET should be optimized for low switching losses paying particular attention to low gate charge for faster switching and low output capacitance to minimize stored energy which must be dissipated each cycle. FET current is equal to the peak output current so a low current FET is sufficient. Maximum voltage stress will occur at high input line. Note that voltage switching spikes in this type of buck regulator are low.

LED ripple current is controlled by the output inductor and is easily calculated by looking at the inductor discharge. Change in inductor current follows ΔI = (VΔt/L) where V is the output voltage, Δt is the off-time of the power switch [(1-duty factor)/65 kHz] or 14.1 µsec, and L is the output inductance. With 14 volts output and a 1mH inductor the change in current is (14 Vdc*14.1 µsec/1 mH) = 197 mA peak-to-peak. Peak inductor current is the average current plus half the peak to peak value or 500 mA+197 mA/2 = 598 mA. The output inductor must support the peak current without saturation. Lower LED ripple current is possible with higher inductance value. Increased inductance should be balanced with possible higher resistance windings which will degrade efficiency since current is flowing through the inductor continuously.

The NCP1216 controls the peak switch current which in a buck regulator is equal to the peak output current. Continuous mode operation maintains constant LED output current over a wide range of input voltage. The dynamic self supply (DSS) feature built in to the NCP1216 reduces start up time and actively controls dissipation. No bias winding is required which means a simple low-cost single-winding inductor is used for this solution. An optional external resistor limits dissipation in the controller by reducing voltage on the high voltage self supply input. Skip cycle operation of the NCP1216 is not needed; therefore pin 1 is tied to the return.

The 100 nF capacitor on the AC input, common mode inductor, 10 µF capacitors and filter inductor comprise the EMI filter. A fusible resistor provides damping for start up and transients as well as protection in the event of failure.

Part Selection

For the power switch, empirical testing reveals a balance between conduction and switching losses to achieve maximum efficiency. A line voltage of 130 V ac will result in 184 Vdc across the FET switch neglecting switching spikes. Selecting a 250 Vdc rated FET provides a stress ratio of less than 75% which enhances reliability. A good starting point is the Fairchild FQPF3N25 which is a 250 Vdc, 2.3 A, 2.2 ohm device with total gate charge of 4 nC and 4.7 pF output capacitance.

Current stress for the common mode inductor is less than 0.2 A. Low resistance will minimize dissipation loss. Toroidal cores of high permeability >9,000 are a good choice and available from several sources. Normal design practice involves two windings with an equal number of turns on each half of the core. Connections are such that mains currents will cancel any net differential current. High impedance to common mode currents is the goal to limit unwanted emissions.

A differential filter inductor may be required as shown in the schematic in a ‘pi’ configuration with two 10 µF bulk capacitors. A 1 mH inductor was used for initial EMI scans and performed well. Current rating is again less than 0.2 A and minimum resistance should be considered when selecting the part. Simple drum type cores are suitable in this application as the AC flux levels are low. Low cost standard devices are available from several sources.

A surface mount 1 mH output inductor was chosen from Coilcraft (MSS1278). This inductor is critical as the AC losses are higher than previously mentioned magnetic devices. Strong fields will be generated and a shielded design is preferred. A closed magnetic path such as an E core or pot core structure could also work well in this application and could be optimized for component values, losses and size. Newer designs include bobbin cores which snap in an outer shield thereby completing the magnetic path to control unwanted stray fields. Many of these designs are surface mount compatible.

The MUR240 provides fast recovery time and low forward conduction voltage for minimal loss in the output rectifier. For higher efficiency in surface mount applications, the MURHS160 is a good choice due to its very short recovery time. As mentioned, slower rectifiers will decrease efficiency and increase heating in the FET switch.

The Vcc storage capacitor can be a low as 1 µF. The NCP1216 DSS circuit biases the IC around 12 Vdc nominal which permits a 25 Vdc rated ceramic capacitor. Stress on this capacitor is low.

Bulk Capacitor Life Analysis

One of the concerns for long life LED lighting applications is that the LED driver circuitry have a reliability in line with the LED and application use profile. Selecting and analyzing the electrolytic capacitors in the application needs to be reviewed and studied to assess operating life. Actual useful life of an electrolytic capacitor is strongly affected by ambient temperature and internal thermal rise due to ripple current acting on internal resistance. The manufacturer's rated life of an electrolytic capacitor is based on exposure to maximum rated temperature with maximum rated ripple current applied. To enhance operating life, a 105 ºC capacitor rated for 2,000 hours was chosen. Operating stresses lower than the rated levels will dramatically increase the useful life of the capacitor beyond the manufacturer's rating by an exponential function.

Formulae for useful life can be found on manufacturer's websites. Note that capacitors rated for 85 ºC and lower life may still be suitable for this application and could result in lower cost.

The pi filter in the circuit is comprised of two 10 µF capacitors and a 1 mH inductor. Both of these capacitors filter the line frequency current and contribute towards maintaining the bulk voltage. Inductor L2 effectively limits the high frequency switching current to capacitor C2. As a result, C3 handles most of the high frequency switching current. In this application, ripple current for this capacitor is approximately 150 mA RMS. For purposes of useful life, assume the ambient temperature surrounding the capacitors is 50 ºC.

The Panasonic ECA-2EHG100 capacitor is rated 2,000 hours at 105 ºC with 132 mA ripple current. Under the conditions listed above, the useful life of this capacitor can be shown to be approximately 73,960 hours based on the ambient conditions listed. It is important in assessing the lifetime to understand the operating temperature of the components in their real world (in-situ) application to properly perform lifetime analysis.

If the two 10 µF capacitors are replaced with a single Panasonic EEU-ED2E220 22 µF capacitor rated 8,000 hours at 105 ºC with 560 mA ripple current the expected useful life is extended to 499,426 hours.

A full lifetime analysis is beyond the scope of the design note but is included here to illustrate the lifetime capabilities of properly selected and sized electrolytic capacitors. For this design, the only electrolytic capacitors are found in the EMI filter.

Configuration Setup

R3 and R6 control the current delivered to the LED load. A low value of sense resistor R6 will reduce dissipation but too low a value will be subject to erratic behavior due to noise. 1.2 ohms is suggested for the 500mA application. The value of R3 can be used for fine adjustments. Values above 40 kohms have no effect.

Performance

Driver efficiency is a function of the LED string forward voltage and input voltage. Figure 2 below shows the effect on efficiency over a range of 3 to 5 LEDs and input voltage spanning 90 to 130 Vac. Increased LED forward voltage and lower input voltage each result in greater duty cycle. Longer conduction times allow more energy transfer per switching cycle thus increasing the delivered power in relationship to the fixed losses per cycle.

Recall for this application schematic, LED current is indirectly controlled via by the switch current. Figure 3 shows a reduction in output current as output LED voltage is increased. For clarity, only data for 115 Vac input is shown. Results for other input voltages are quite similar.

Figure 4 shows results for conducted emissions per EN5022 Class B limits. The plot shows this driver passes requirements with ample margin. The dashed line represents typical 6 dB margin from the required limit. Note that the NCP1216 has frequency modulation of the switching frequency to reduce the EMI signature.

The common mode inductor may not be required. Required filtering is highly dependant on a particular implementation therefore EMI tests should be repeated with the final printed circuit board in the application form factor to validate performance.

As mentioned above, LED current consists of a constant current with superimposed ripple. Figure 5 depicts LED current as measured with a DC coupled current probe at 300 mA per volt. The image shows about 450 mA constant current with 174 mA peak to peak AC component. This represents about 19% peak to average ripple current. The narrow spike is partially related to noise pickup in the current probe.

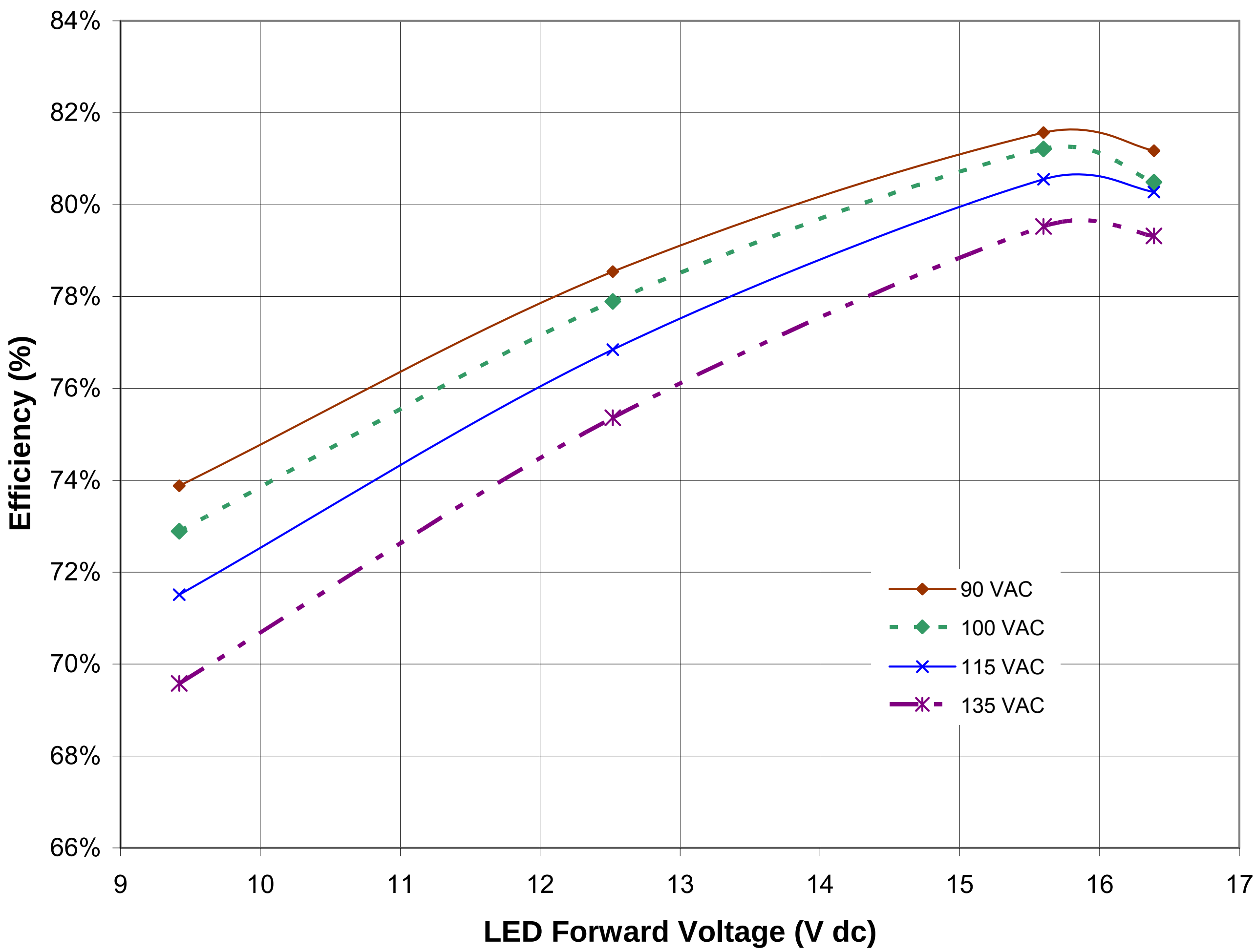


Figure 2: Efficiency across Line and Forward Voltage Variation

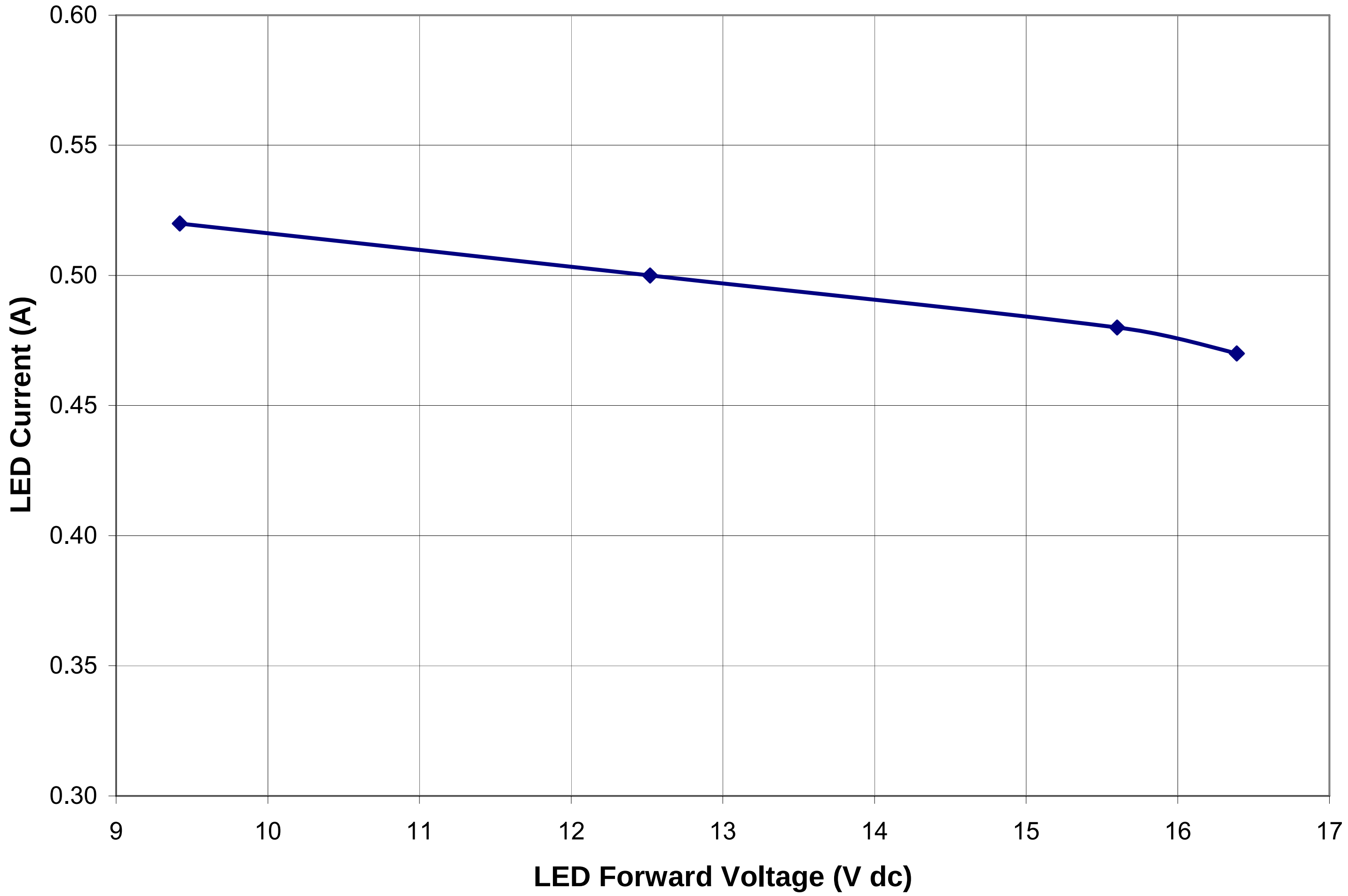


Figure 3: Current Regulation across Forward Voltage (Vin=115 Vac)

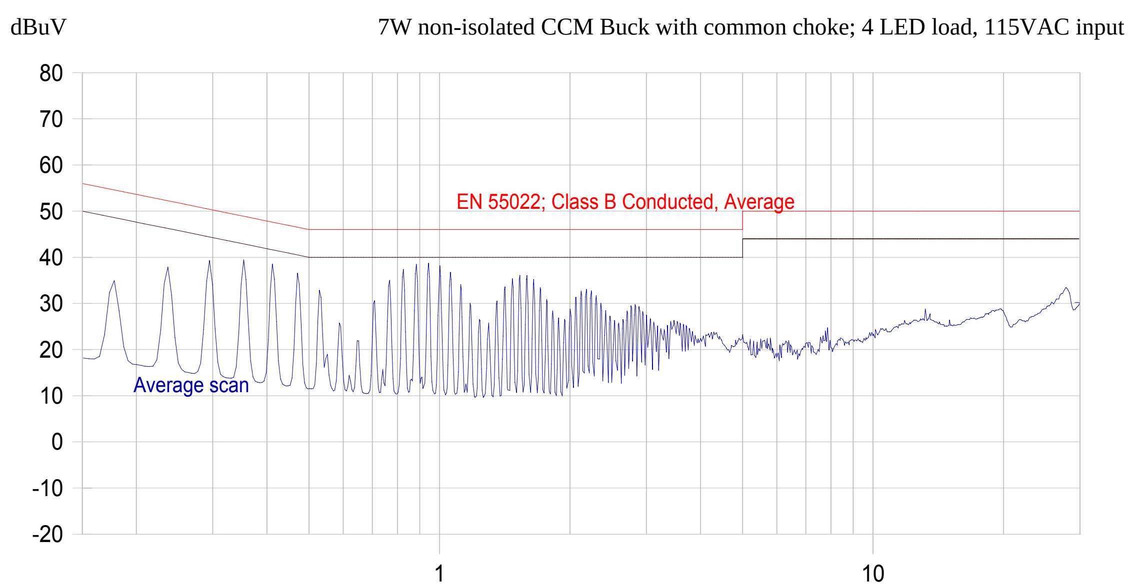
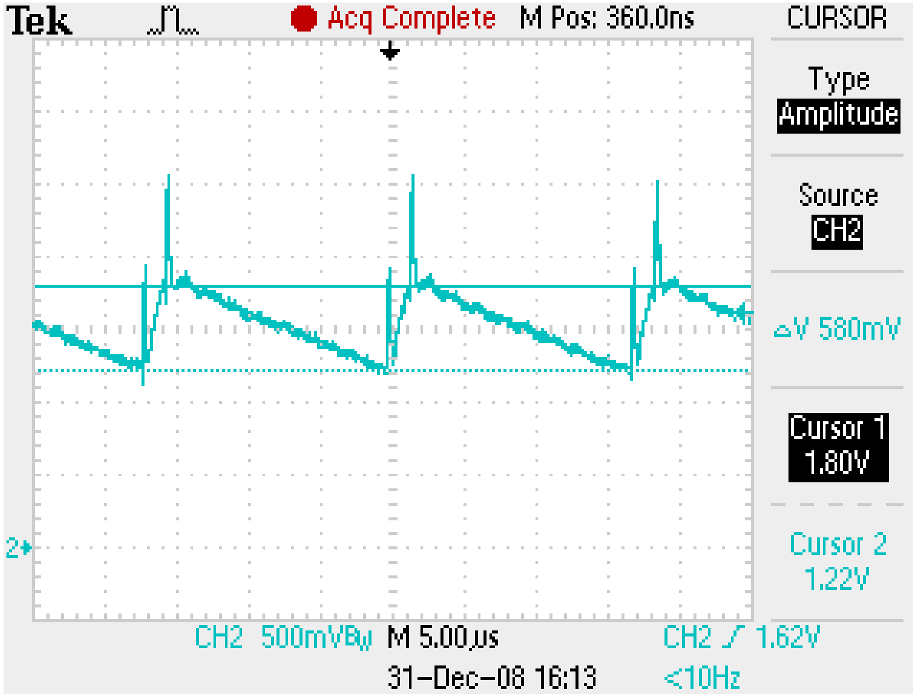


Figure 4: Average Conducted EMI Scan



Channel 2 scale (300 mA/V)

Figure 5: Output Current Waveform

Bill of Materials

Ref Designator	Part Number	Manufacturer	Description	Package
C1	ECQU3A104ML	Panasonic	0.1uF, 275V X cap	thru hole
C2,C3	ECA-2EHG100	Panasonic	10uF, 250V, 105C	radial
C4		Any	1nF, 50V ceramic	thru hole
C5		Any	1uF, 25V ceramic	thru hole
D1, D2, D3, D4	1N4004	ON Semiconductor	1A, 400V	axial
D5	MUR240G	ON Semiconductor	2A, 400V, 50nS	axial
L1		Any	1mH common choke	thru hole
L2	RFB1010-102L	Coilcraft	1mH, .6A, 1.45R	radial
L3	MSS1278-105KL	Coilcraft	1mH, 1A, 1.33R	SMD
Q1	FQPF3N25	Fairchild	250V, 2.3A, 2.2R	TO-220
R1	NFR25H0004708JR500	Vishay	4.7 ohm, 1/2W fusible	thru hole
R2		Any	1 meg, 1/2W	thru hole
R3		Any	11K, 1/4W	thru hole
R4		Any	10K, 1/4W	thru hole
R5		Any	1K, 1/4W	thru hole
R6 (500mA output)		Any	1.2R, 1/4W	thru hole
R6 (700mA output)		Any	0.9R, 1/4W	thru hole
U1	NCP1216P65G	ON Semiconductor	PWM controller	DIP7

Breakdown of Component Losses

Device	Power dissipation (W)	Loss Contribution
R1 input resistor	0.09	4.3%
L1 CM inductor	0.003	0%
D1-D4 input diodes	0.219	10.6%
L2 differential inductor	0.03	1.4%
R4 bias resistor	0.026	1.3%
U1 controller	0.2	10%
R6 sense resistor	0.026	1.3%
Q1 power switch	0.624	30.1%
D5 output rectifier	0.357	17.2%
L3 output inductor	0.358	17.2%
Remaining parts	0.14	6.7%
Total	**2.07 W**	

Conclusion

The information presented in this design note covers factors needed to construct a non-isolated LED driver. The circuit can be tailored for specific LED ratings to create a reliable long-life lighting solution.

Wider pulse width operation is possible with a tapped output inductor design. See ON Semiconductor application note AND8318/D. Wider pulse width enhances performance and may be more suitable for operation at high input line voltages. An added benefit is reverse recovery current in output rectifier D5 is reduced. This reduction in recovery current is a result of a small amount of leakage inductance between the two sections of the tapped inductor. Lower recovery current will reduce losses and consequently increase efficiency.

Suitable multi-winding inductors are available from vendors such as Coilcraft. The series MSD1278 SEPIC inductor works well in this application. Custom designed magnetics is another option which may provide better mechanical features and lower cost. Note an output capacitor is needed with a tapped inductor approach due to discontinuous output current.

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