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TND398/D

Offline High Power Factor Triac Dimmable LED Driver Intended for ENERGY STAR® Commercial and Residential LED Luminaires

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TECHNICAL NOTE

Overview

This reference document describes a built-and-tested, GreenPoint® solution for a 13 W nominal constant current power factor corrected offline LED driver. This is intended for solid state lighting (SSL) applications such as commercial and residential LED downlights and spotlights that require high efficiency, power factor correction and triac dimming control. The power supply design is built around ON Semiconductor's NCL30000 critical conduction mode fixed on-time flyback controller. The secondary side regulates a 350 mA constant current capable of driving a string of 1 W phosphor converted "white" LEDs. This reference design is optimized for driving 12 LEDs at 350 mA but the design is adaptable to accommodate a range of 4 to 15 LEDs in series with minor component modifications. The maximum power capability of this specific design is 15 W. The design is flexible and robust with output open and short circuit protection as well as optional thermal shutdown in the event that the operating temperature is exceeded.

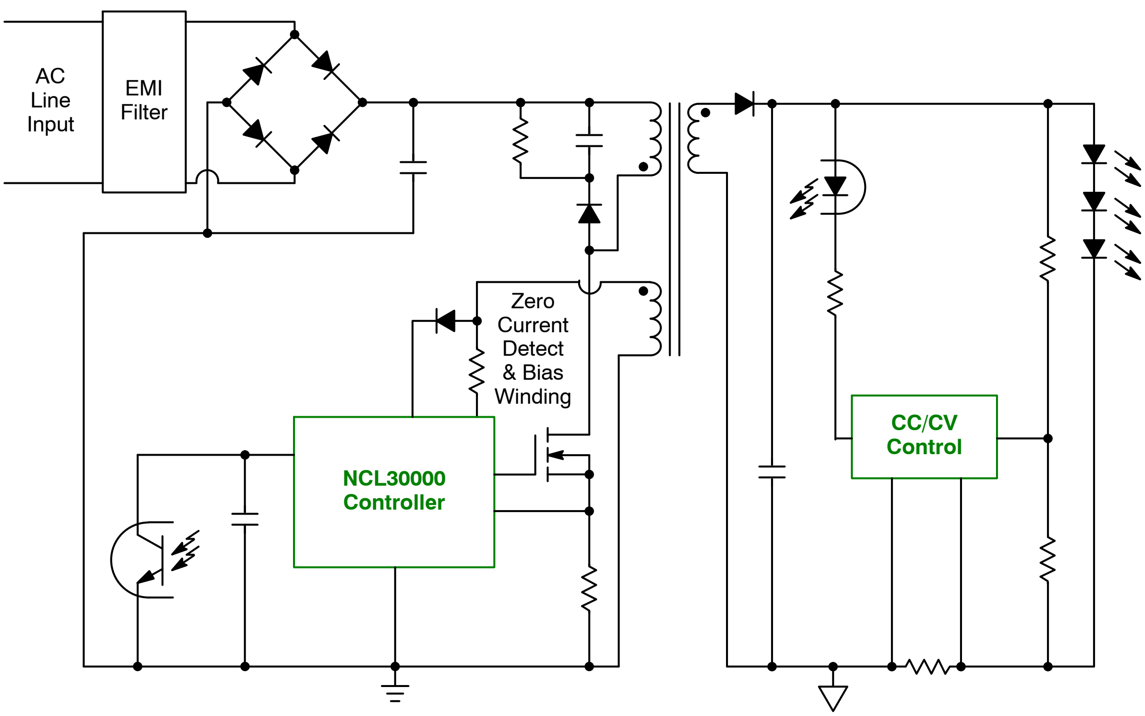

Figure 1. Simplified Block Diagram

Background

It is estimated by the International Energy Agency that more than 19% of electrical energy demand globally is used for lighting. As a result, there has been significant effort globally in replacing in-efficient incandescent light sources with higher efficiency solutions. In fact within the EU and the United States, sales of the most inefficient incandescent light sources are already starting to be phased out and this will accelerate over the next 5 years. Much of the focus in curbing this demand has been in programs to drive adoption of compact fluorescent lamps. CFL adoption has been successful in many lighting applications, but incandescent bulbs remain the product of choice in applications that require line dimming due to their superior dimming control characteristics. This is true for accent as well as primary lighting in many commercial, residential and retail lighting applications. Moreover dimmed incandescent bulbs save energy as they allow the user to set the light level for the appropriate ambient level.

An alternative which has been gaining significant attention is white LEDs. LED lumen output and efficacy – the measure of lumen output versus input power - continues to make significant progress year over year while, at the same time, the cost in terms of $/lumen is falling. Commercially available 1 W warm white LEDs can generate 90 lumens with an efficacy of >80 lm/W. For reference, a standard 60 W incandescent bulb generates ~800 lm at an efficacy of ~14 lm/W, which is approximately 5x lower. Comparing raw source efficacy does not tell the whole story. LED lumen output does drop with temperature and LEDs require a driver to convert AC power to a DC current to drive the LEDs and there are also optical fixture losses. Since LEDs are directional in nature, in applications like downlights, desk lamps, and under-cabinet lighting that do not require omni-directional light, the lower optical losses of an LED based fixture can be lower than a comparable incandescent bulb. So in a completed and an installed downlight for example, a properly designed LED based product can consume 1/3 to 1/4 the power of an equivalent incandescent fixture while delivering comparable light output.

Beyond energy savings, high brightness LEDs can have operating lifetimes greater than 50,000 hours when properly designed and operated which dramatically reduces the labor cost of replacing bulbs. For example, if we look at a full service restaurant and assume 16 hours a day of operation, 50,000 hours is equivalent to more than 8.5 years of use. As a result when looking at total cost of ownership (energy plus maintenance) for high use applications, LEDs offer a very favorable payback period.

Applicable Standards

To help promote energy savings, the US Department of Energy has developed and released the ENERGY STAR Standard for Solid State Lighting Luminaires. This voluntary standard establishes a set of coherent requirements for a variety of commonly used residential and commercial luminaries. These requirements include minimum lumen output, overall efficacy, reliability objectives, light color temperature and a series of other critical system level requirements. The intent being that any luminaire that meets the ENERGY STAR standard would achieve comparable light output in application to the incumbent light source while achieving energy savings.

The current standard, Version 1.1 was finalized in December 2008 and covers 15 diverse residential and commercial lighting applications ranging from residential under cabinet lighting to commercial wall washers that would immediately benefit from solid state lighting in terms of reducing energy consumption. This standard does not explicitly establish power supply efficiency requirements but it does include a minimum power factor (PF) of 0.7 for residential applications and 0.9 for commercial applications regardless of the power level. This is a departure from the ENERGY STAR CFL bulb standard where the minimum power factor is 0.5.

There is an overall requirement within the standard which establishes a luminaire efficacy; effectively this system-based standard includes the LED selected, the in situ operating temperature, the optics, and the power conversion efficiency of the driver. The luminaire developer can thus make tradeoffs among the LEDs selected, the optics used, the thermal management solution as well as the driver topology and design to meet the overall requirements. The table below highlights the key system requirements for recessed downlights for residential and commercial applications under Version 1.1.

Table 1. KEY RECESSED, SURFACE AND PENDANT DOWNLIGHT CRITERIA

Aperature Size (in)	Minimum Lumen Output	Efficacy (lm/W)	Correlated Color Temperatures (CCT)	
≤ 4.5	345	35	2700K, 3000K, 3500K	Residential
> 4.5	575	35	2700K, 3000K, 3500K, 4000K, 4500K, 5000K	Commercial

NOTE: Power factor of residential fixtures is relaxed from ≥0.9 to ≥0.7.

The most common downlights fall into the larger aperture category. Note beyond the power factor differences between residential and commercial applications, designers have the flexibility to use neutral as well as warm white LEDs. As can be seen from the minimum requirements, when converting minimum lumen output to input wall plug power, this establishes a maximum input power threshold of 16.4 W.

Since there is no explicit standard for LED driver efficiency a good proxy is the ENERGY STAR External Power Supply (EPS 2.0) standard. This established efficiency targets for single output power supplies as a function of the rated output load. The intent of the EPS 2.0 standard is to establish minimum efficiency limits that represent true energy savings over products on the market, but still be achievable for mainstream applications. While not a hard and fast rule, the intent of the standard is to establish limits that represent top 25% performance. EPS 2.0 is not necessarily a perfect proxy for offline LED drivers. One of the focuses of EPS 2.0 is standby power, which is not relevant for the majority of LED lighting applications. In fact, the LED Luminaire guidelines explicitly states that in off mode the power consumption should be zero except in cases were there are built in controls such as occupancy sensors. Moreover the EPS 2.0 standard is looking at efficiency across the whole operation range of the supply and averages the efficiency at 4 data points, namely 25, 50, 75 and 100% of full load. The 25% and 50% points are really not critical for luminaires as the load is normally fixed to a set number of LEDs and a prescribed drive current. Even in cases where the user could control the luminaire light output like a desk lamp, as the LED current is reduced, the LED forward voltage would actually drop, the junction temperature will drop and the efficacy (lm/W) of the LED improves. On the other hand, efficiency at the 75% and 100% points is very important. For a fixed drive current, the LED forward voltage has a wide window of typically ±20% or more due to manufacturing tolerance, lot-to-lot variation, and operating temperature. Finally unlike the LED Luminaire Standard, EPS 2.0 does not require any power factor correction until the input power is >100 W. Even with these caveats, EPS 2.0 is a good benchmark as it establishes limits based on good design practices for high volume power supply circuits. The equation below is the minimum average efficiency for standard power supplies rated between 1−49 W:

$$\text{Efficiency} \geq 0.0626 \times \ln(P_{no}) + 0.622$$

Measured at 25, 50, 75, & 100% of rated nameplate output power P_{no}.

So for a 12 W rated supply the minimum efficiency to be compliant is 77.7% which increases to 79.1% for a 15 W rated supply. Since the LED Luminaire standard is based on input plug efficiency, it is necessary to translate the driver efficiency target into an effective LED load. To add some design margin, a minimum efficiency of 80% is targeted.

$$\begin{aligned}\text{LED Load} &= \text{Wall Plug Maximum} \times \text{Efficiency}\\ &= 16.4\ \text{W} \times 80\% = 13.1\ \text{W}\end{aligned}$$

Now a maximum load design target has been established. LED efficacy is a function of the LED manufacturer performance as well as drive current and operating temperature. A constant current of 350 mA was selected for this GreenPoint design to support the most common high brightness power LEDs on the market. One other consideration is that the luminaire developer can select from a wide range of LEDs and the higher the efficacy of the LEDs selected, the fewer LEDs are required so this is another reason that the efficiency of this GreenPoint design needs to be highly efficiency from 50−100% of the rated load. As LED efficacy improves, the same basic power supply design can be easily adjusted to drive fewer LEDs resulting in much higher fixture efficacy than the minimum.

Approach

Now that basic design guidelines have been established, other system considerations must be taken into account related to the end application needs. As mentioned, while not required from the standard, compatibility with existing line dimming infrastructure is important so this design will be optimized for Triac wall dimmers. Triac dimming represents a whole host of challenges, but one which could easily be overlooked is that the driver should be able to start and run from a low chopped AC input waveform. Moreover the size of the power supply has to be such that it fits within the junction box of the downlight fixture. A human factors requirement that needs to be addressed is startup time. While LEDs generate light virtually instantaneously, the driver has to be designed for a specific startup time. Any LED fixture should be at least as good as or better than a typical CFL product so we can use that as a baseline. The ENERGY STAR CFL bulb requirement has a maximum startup of 1 second under normal conditions so for the LED driver the design objective is set at 0.5 sec. Since this is designed for either residential or commercial applications, the more challenging specification was targeted. The table below lists the key design objectives of this GreenPoint reference design.

Table 2. SUMMARY OF DESIGN OBJECTIVES

Parameter	Design Specification	Comment
Maximum Output Power	15 W Maximum	Vin = 115 Vac
Output Current	350 mA ±5%	
Galvanic Isolation	Yes	
Forward Voltage Compliance Range	> 3:1	
Full Load Efficiency	> 80%	
Power Factor	> 0.95	Commercial Level, minimum is 0.90
THD	< 20%	
Startup Time	< 0.5 seconds	Vin = 115 Vac, CFL Bulb Spec < 1 sec
Triac Dimming Range	Minimum 10:1 (35 mA)	
Open Circuit Voltage	< 58 Vdc	UL1310 Class 2 < 60 Vdc

To achieve the high power factor, efficiency target and compact size it was necessary to employ a high power factor single stage topology. Given the low power target, need for high efficiency and compact size a traditional two stage (PFC boost plus flyback) was out of the question so a critical conduction mode (CrM) flyback based on the NCL30000 CrM flyback controller was used. Designing for power factor (PF > 0.95) allows easy compliance with the commercial lighting requirement of the SSL Luminaire standard and it also makes the input current waveform of the driver appear like a resistive load. This is very important for Triac dimming compatibility as these types of dimmers are intended for incandescent lamps which look like a resistor. The basic current waveform of an optimally designed single stage CrM flyback is illustrated in Figure 2. As seen the input current (blue trace) is in phase with the input voltage waveform.

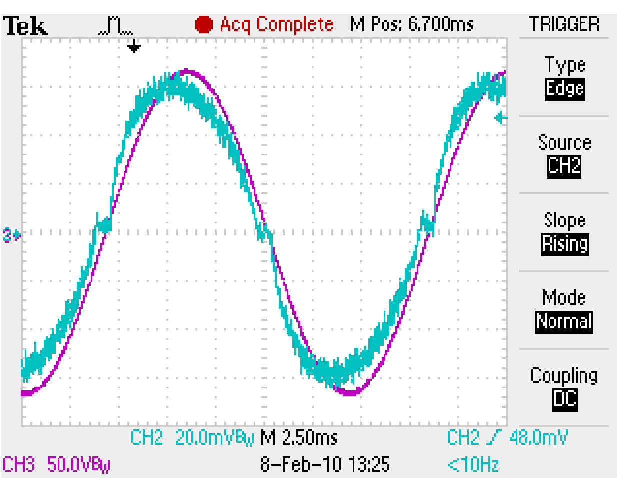

Figure 2. CrM Flyback Input Waveform

As seen in Figure 1, there is also a CCCV control block on the secondary side of the isolated flyback. This has two primary functions; first it tightly regulates a constant current of 350 mA and provides feedback to the primary side to adjust the on time to regulate constant current through the LEDs. In addition in the event of an open circuit, it enters a constant voltage control mode which regulates a fixed voltage in the event of a fault. The open voltage is regulated to be below the 60 Vdc maximum voltage limit of a class 2 power supply. Finally in the event the output is inadvertently short circuited, the power is limited to avoid damage to the LED driver.

Complete details of the GreenPoint design are available at onsemi.com as part of the NCL30000LED1GEVB data set including bill-of-material, schematic, Gerber files and demo board manual. Details of the design are discussed in the NCL30000 datasheet and the two accompanying application notes. The Power Stage Design Application Note discusses the key considerations for designing a CrM flyback while the Designing for Triac Compatibility Application Note discusses all the considerations needed for implementing line dimming control.

Results

In this section, compliance to the design objectives will be illustrated in the following plots and graphs. All the initial design objectives highlighted in Table 2 were exceeded for this reference design. Figure 3 illustrates the power factor and input current total harmonic distortion of the LED Driver across the line voltage range of 90−135 Vac. As indicated the CrM flyback topology achieves excellent power factor and low distortion. This performance exceeds the minimum commercial requirement of 0.9 and as well as the THD objective of < 20%.

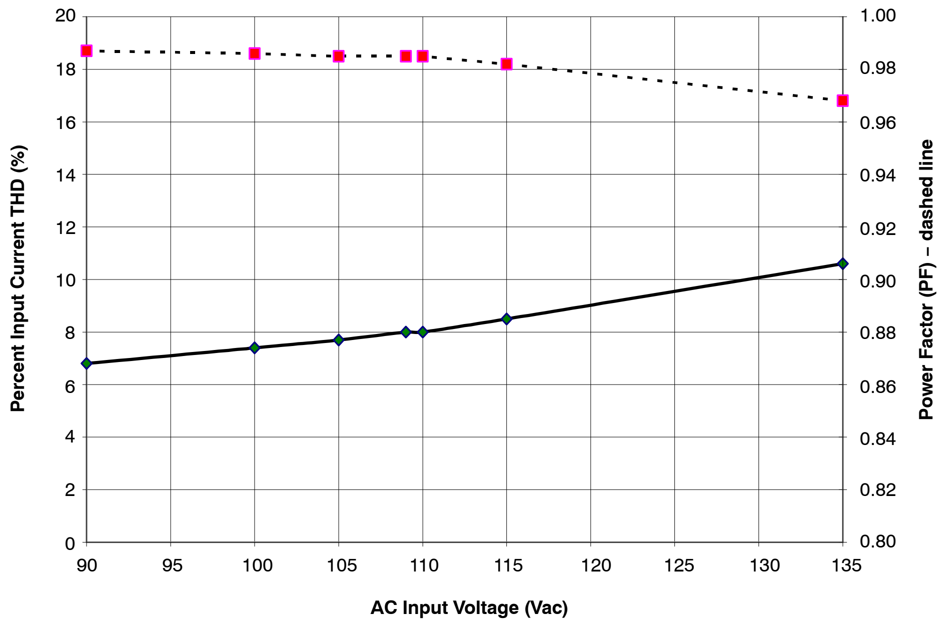

Figure 3. Power Factor and THD across input line voltage (Vf = 37.8 V)

Figure 4 illustrates the efficiency of the LED driver for various load conditions representing different LED forward voltages up to a maximum Pout of 15 W. By averaging the 25%, 50%, 75% and 100% points the overall average efficiency measured is 80.7% and in the critical region between 50−100% the efficiency ranges from 81.1 – 82%. This exceeds the 80% efficiency design objective as well as the EPS 2.0 limit of 79.1% for a 15 W supply. The losses include 15 ohm current limiting resistors in the input EMI stage necessary to support Triac dimming.

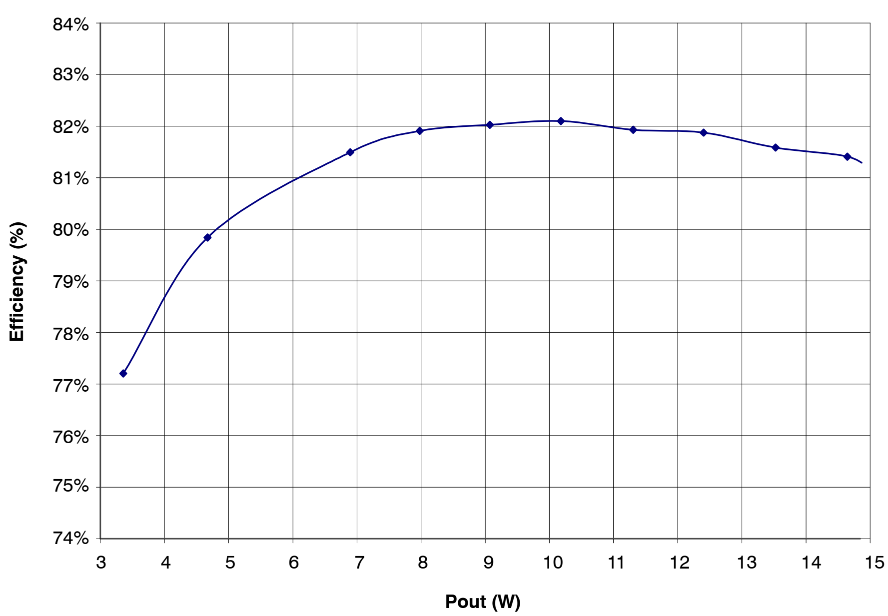

Figure 4. Efficiency versus load (Vin = 115 Vac)

Figure 5 illustrates the current regulation across a range of LED forward voltages. This GreenPoint design is power limited to 15 W nominal and has a nominal current regulation of 350 mA. The intent was to regulate a fixed current across a minimum 3:1 forward voltage ratio to allow it to handle a range of LEDs. This curve shows three primary regions of operation; a constant current range from approximately 10−42 V where the current regulation is precisely controlled, above 42 V nominal, the regulation control switches to primary side control where the power is limited by the on-time, and finally a constant voltage region where the output voltage is fixed. The constant voltage point is below the maximum 60 Vdc rating targeted by the specification.

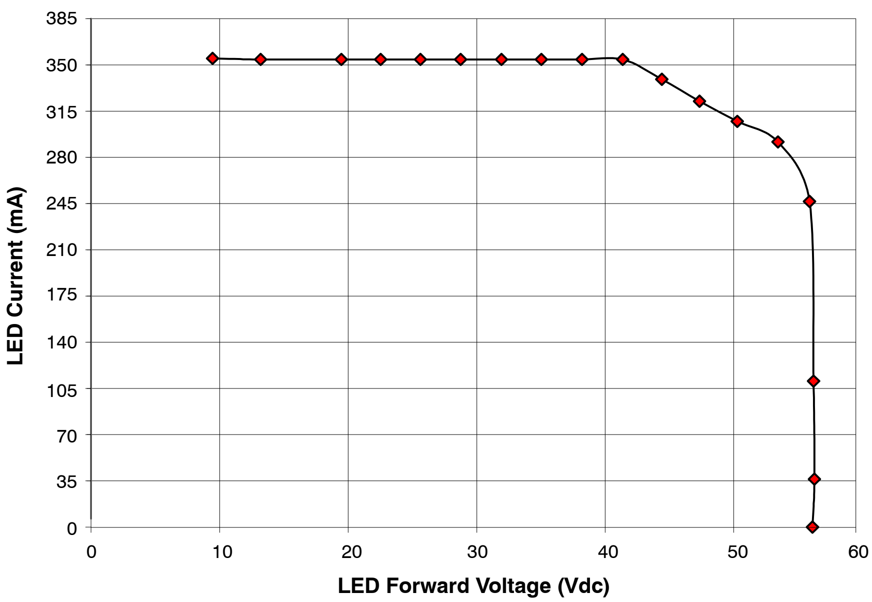

Figure 5. Current Load Regulation (Vin = 115 Vac)

Figure 6 illustrates the dimming range achieved with a 12 LED load (Vf = 37.8 V @ 350 mA) with a range of off-the-shelf dimmers. As illustrated this design is intended to provide full power when the dimmer is in the maximum position represented by conduction angles. This is in contrast to a standard incandescent bulb which even when the dimmer is at the maximum conduction angle, has reduced light output. Depending on the dimmer used the dimming range extends down in some cases until the LED current was virtually 0 and in almost all cases, dimming down to at least 5% was achieved. The exception to this is illustrated by the dashed line, which represents the performance of an electronic dimmer with trailing edge control. This dimmer is intended for driving low voltage electronic transformers and this one illustrated a very high minimum conduction angle of ~55 degrees.

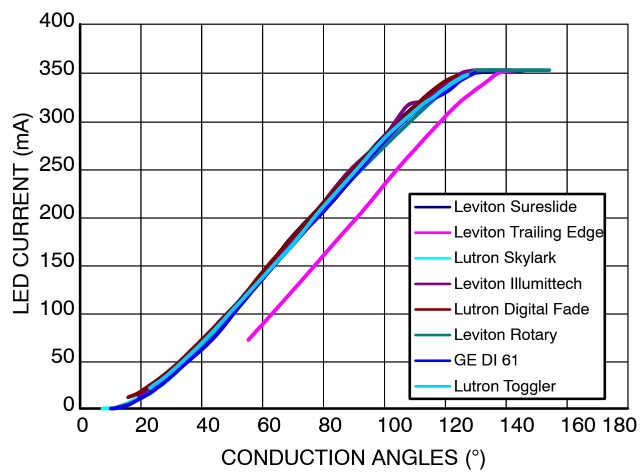

Figure 6. Dimmer Control Range (Vin = 115 Vac, 12 LED load)

Figure 7 illustrates a waveform of startup. Channel 3 is the AC input and Channel 2 is the regulated current to the LEDs. There are two distinct regions covering the startup of the power supply and the stabilization of the control loop. Under normal conditions, the startup time is approximately 300 msec to get to 50% of full load. By design, power factor control loops have inherently low bandwidth, this is also true with a single stage topology, and as a result it takes another 300 msec to completely stabilize the current regulation loop.

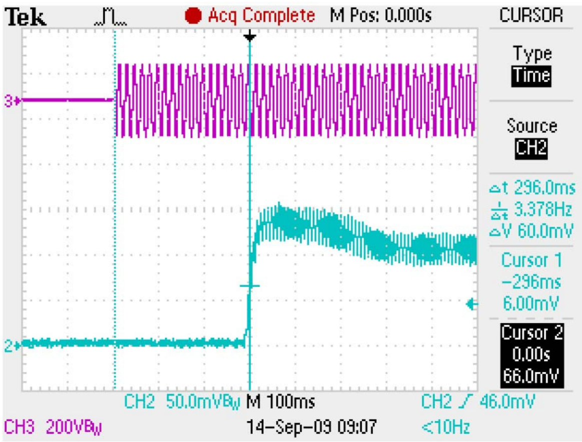

Figure 7. Startup Time (Vin = 115 Vac, 12 LED load)

Summary

Designing offline LED drivers that meet all the requirements of next generation solid state lighting products presents numerous challenges. As illustrated, all the key performance objectives were achieved based on a single stage architecture which meets the most stringent power factor requirements at very low output power levels. Moreover the controller based design gives system developers the flexibility to scale the power up or down to address higher power applications. This approach allows designers to keep up with ever improving LEDs that will allow them to design luminaires with fewer LEDs while still achieving the expected light output levels.

Reference Materials

[1] ENERGY STAR Program Requirements for Solid State Lighting Luminaires, Version 1.1
[2] ENERGY STAR Program Requirements for CFLs
[3] NCL30000 Power Factor Corrected Dimmable LED Driver
[4] AND8448 Configuring the NCL30000 for TRIAC Dimming
[5] AND8451 Power Stage Design Guidelines for the NCL30000 Single Stage CrM Flyback LED Driver
[6] NCL30000 Evaluation Board Documentation
[7] NCL30000LED1GEVB Manual

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