

Configuring the NCL30000 for TRIAC Dimming

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APPLICATION NOTE

Introduction

As LED lighting starts to enter the mainstream of general lighting it is important to be compatible with the existing line dimming infrastructure. This has been one of the limitations of wider acceptance of CFL bulbs as many applications require dimming and the user expectation of the dimming control range is that it is comparable to the incandescent lamps which are being replaced. There are two main types of phase cut dimmers – leading edge (triac based) or trailing edge (transistor based). Trailing edge dimmers were specifically developed to be compatible to the capacitive input of electronic transformers used for driving low voltage halogen bulbs. Nevertheless, given that triac dimmers are widely used, there is strong interest in triac dimmable LED fixtures and bulbs. This application note describes the basics of line dimming and describes how the NCL30000 single stage power factor corrected flyback controller can be optimized to control the drive current of an LED string with a standard wall dimmer.

Basic Phase Cut Dimmer Operation

Dimmers intended for incandescent bulbs reduce the amount of energy delivered by blocking or cutting away part of the delivered AC waveform. Since incandescent bulbs look like resistive loads, the power delivered is proportional

to the relative amount of the full AC waveform allowed to pass. Leading edge (Forward) phase cut dimmers utilize a triac or bidirectional thyristor to control the voltage delivered to the load. Due to the nature of the triac, the conduction time starts some time after the beginning of the half sine wave and continues until the zero crossing. The delayed turn on continues for each half cycle of source power. One unfortunate characteristic of these dimmers is that they have an abrupt current step. This is not a problem for incandescent bulbs as the filament has a thermal time constant which integrates out the energy pulses providing constant illumination.

The voltage applied to the bulb is gated on for a particular fraction of each half cycle of the incoming waveform. This is illustrated in Figure 1 and is referred to as the conduction angle when expressed in degrees. 180° represents no phase cutting. The maximum conduction angle varies depending on the dimmer manufacturer, but in most cases it ranges from 120° – 160° . Decreasing the conduction angle reduces the applied RMS voltage and consequently the amount of power delivered to the bulb. Conversely, increasing the dimmer control upward increases the conduction angle and therefore the available voltage to the bulb thus increasing the brightness.

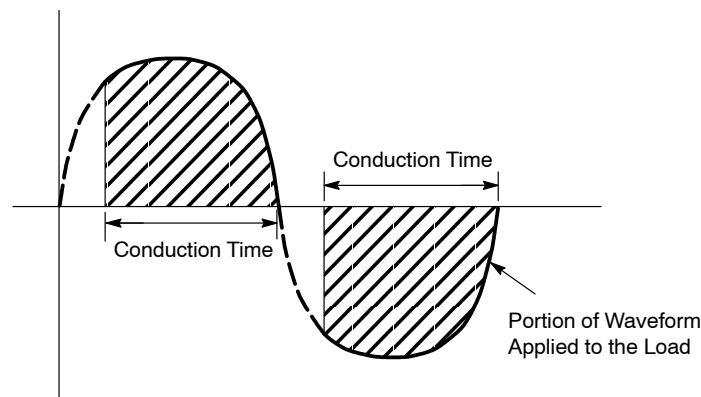


Figure 1. Leading Edge Phase Cut Waveform

Once the triac has fired, sufficient load or hold current is required to keep the triac latched on and maintain conduction over the entire half cycle of AC input. If the load current were to drop to zero after the triac is fired, it can switch off and then fire again resulting in flicker. The abrupt triac switching can create stress in electronics circuits and may result in erratic operation. Anyone who has inadvertently connected a standard non-dimmable CFL bulb to a leading edge dimmer can see this flicker or pulsing effect regardless of the dimmer position. Moreover, triac dimmers also have a minimum load required to operate properly. As a result depending on the dimmer position, it may be necessary to slide up the dimmer until the incandescent turns on.

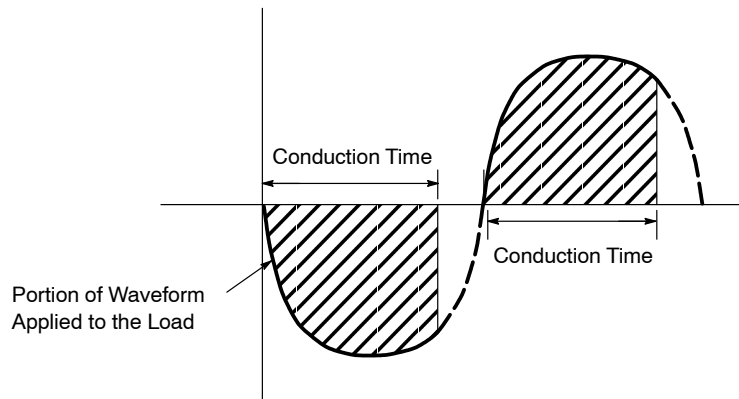


Figure 2. Trailing Edge Phase Cut Waveform

Steps to Designing a Phase Cut Dimmable LED Driver

Designing an LED driver circuit to successfully interface with phase cut dimmers can be broken down into several steps. The first step is the LED current should be proportional to the input RMS voltage as controlled by the conduction angle of the dimmer. A smooth reduction in LED current as the dimmer conduction angle is reduced provides satisfactory performance for a user. While the range of control is affected by the dimmer characteristics and will vary from one dimmer to another, ideally the dimming response should utilize the whole range of the knob or slider to giving the end user the best control.

The LED driver should emulate a resistive load enabling proper operation of the dimmer as the current will be in phase and proportional to the line voltage. A completely resistive load results in a maximum power factor of 1. Designing the LED driver with a true high input power factor characteristic means the voltage and current will be nearly in phase which supports proper dimmer operation. While it is possible to improve power factor with a 'valley-fill' circuit, this type of circuit does not draw current from the ac line throughout the whole switching cycle and as a result there is a region where there is no holding current which is problematic to maintaining the triac in a latched state.

A second type of dimmer is based on transistor switches which start conducting at the beginning of the half sine wave. After conducting for the prescribed time or conduction angle, the transistor turns off terminating the AC waveform applied to the load. This type of dimmer is referred to as trailing-edge (reverse) phase control and is characterized by more gradual current changes as the electronic load follows the smooth rise at the beginning of a sine wave and then after switching off, the energy stored in the inductors and capacitors naturally decays to zero. The waveform is illustrated in Figure 2.

Any electronic circuit has some effective capacitance and the input capacitance of the LED Driver introduces high peak currents when the triac turns on. Capacitor value in the EMI filter stage should be kept to a minimum as the high peak line current excites line inductance and the EMI filter inductance creating resonant currents which interfere with triac operation. Careful consideration must be given to reduce the level of line current peaks.

Once the dimmer triac has turned on, a minimum current must be maintained or the triac will switch off. Most dimmers are rated for 40 to 60 W minimum load. This is the reason that some dimmers need to be turned up before an incandescent lamp will turn on. Since an LED lamp can present a load that is only 10–20% of the incandescent that is being replaced, this may present a problem. For example, the LED equivalent of a 60 W incandescent may represent only a 10–15 W equivalent load. This may not be a problem when multiple LED lamps are on a dimmer circuit. As a result, with some dimmers the range of control of the LED lamp may not be as wide as the incandescent being replaced.

Finally, care is needed to ensure the controller circuitry maintains proper biasing levels. Reducing the peak input voltage with low conduction angles cuts back on the available power for biasing. An examination of V_{CC} bias

operation over the entire range of dimmer conduction angle should be considered.

Dimmer Characteristic and Constant On-Time

Conventional dimmers intended for incandescent lamps control brightness by modulating the AC waveform delivered to the bulb. Controlling brightness of an LED lamp with a dimmer is significantly more complex than controlling an incandescent bulb. The LED power converter includes a feedback control system which is usually designed to maintain a constant level by compensating for a range of LED load power and line voltage variations. One would expect that if part of the input waveform was missing the control loop would compensate by drawing more power during the conduction-time to maintain constant LED current.

Some method of directly or indirectly sensing the input voltage is necessary to implement dimming control. Ideally, the dimmer operating in concert with the LED lamp would provide full current to the LEDs at the maximum dimmer setting and smoothly reduce LED current and therefore brightness at the setting is reduced as shown in Figure 3.

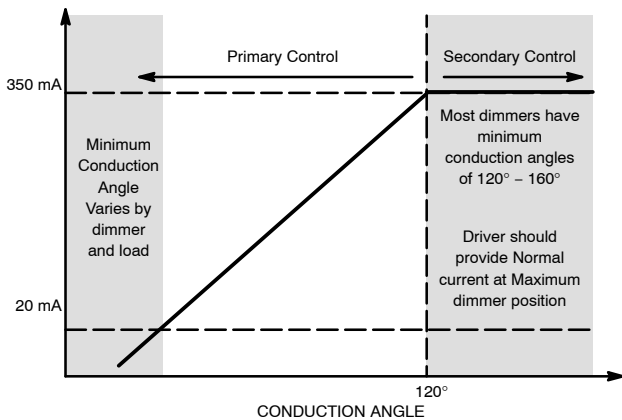


Figure 3. Dimming Control Response

For triac dimming control, the NCL30000 is configured to combine accurate secondary side regulation to provide a constant current at maximum dimmer position with primary side control that naturally limits the power as the conduction

angle is reduced thus emulating the operation of an incandescent bulb. To achieve this response, the control loop is modified to revert from secondary side control to primary side control based on a fixed power relationship as the conduction angle is reduced. Given a virtually fixed load like an LED, the on-time is inversely proportional to the input voltage. The maximum on-time of the NCL30000 can be configured to provide control of the regulation point. If the maximum on-time control is set to a level just below the nominal line voltage, output LED current will decrease below this set line voltage as the FET on-time is limited to a level insufficient to maintain full LED current.

Adjusting the maximum on-time capacitor will provide primary side dimming control with smooth predictable brightness control. This works equally well from either a leading or trailing edge dimmer since the control is solely based on the RMS input voltage. The capacitor selection is based on the dimming inception voltage and a given LED load. The formula shown below gives an approximation of the maximum on-time or Ct capacitor.

$$C_t \approx \frac{(4.94 \cdot L_{pri} \cdot P_{out} \cdot I_{charge})}{(\eta' \cdot V_{pk}^2 \cdot V_{CT(max)})} \cdot \left(\frac{V_{pk}}{N \cdot V_{out}} + 1 \right) \text{ (eq. 1)}$$

Where L_{pri} is the transformer primary inductance, P_o is the output power, I_{charge} and V_{ctmax} are from the NCL30000 specification, η' is transformer/secondary efficiency, V_{pk} is the peak of the dimming inception voltage, N is the transformer turns ratio, and V_{out} is the output voltage. Some empirical adjustments to this value may be required to match the load since the equation is based on a target efficiency and the relationship with a chopped AC waveform and sinusoid input waveform are not exact.

Experimentation with the NCL30000LED1GEVB demonstration board using many 115 V ac dimmer shows 470 pF provides acceptable performance with a 12 W load. For 230 V ac applications a capacitor of 180 pF is required on the NCL30000LED2GEVB demonstration board. Once the dimming relationship has been defined for triac dimming by setting the maximum on time, it is necessary to look at the design of the input EMI network to assure compatibility with triac dimming.

Input Network

Operation of a standard commercial triac dimmer powering a 15 W incandescent lamp is shown in the image below. The top trace is the voltage across the load at 100 V/div and the bottom trace is the current through the load at 167 mA/div. The delay in turning on the triac and resultant conduction angle is clearly displayed.

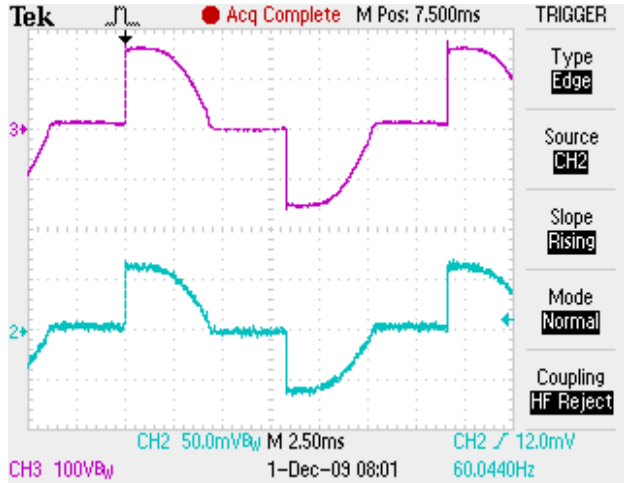


Figure 4. Typical Input Current/Voltage Waveform of a Dimmed 15 W Incandescent

Even if a perfect power factor corrected driver existed such that the input waveform looked like an incandescent bulb, an EMI filter would be required. Transient current introduced by the triac step excites the natural resonance of the EMI filter inductors and capacitors. If this resonant behavior results in the input current falling below the triac holding current the triac will turn off. After a short delay, the triac will usually turn back on once again exciting the same resonance. This series of events can repeat many times over

the span of one half cycle of the input power waveform. This cycling results in visible LED flickering.

To illustrate this effect, a 100 nF capacitor was connected in parallel with the 15 W incandescent bulb in the example above to emulate what an LED driver load might look like. The building wiring coupled with the capacitance results in a resonant circuit as seen in Figure 5. This is the same configuration as Figure 4 but we can now see the triac turning on and off several times each half cycle of the input waveform as a consequence of added capacitive load.

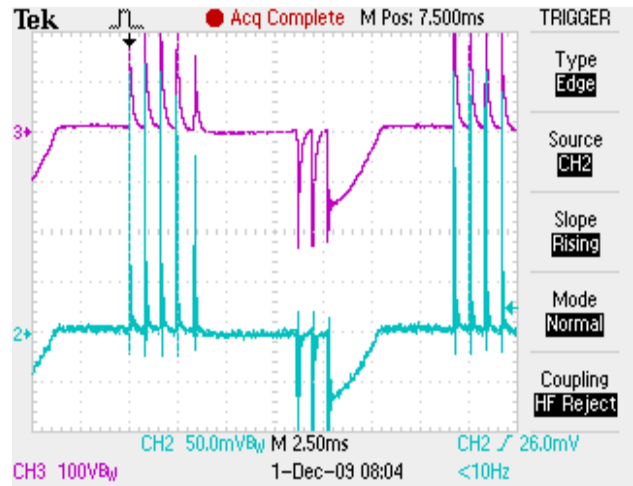


Figure 5. Input Current Voltage Waveform with 100 nF/15 W Incandescent Load

The result of this condition is the load will receive much lower average power and create disturbance on the power line. Figure 6 shows a simplified schematic of a triac dimmer and we can see that the series inductance of the dimmer and line wiring result in a resonant circuit with the input capacitance of the LED driver.

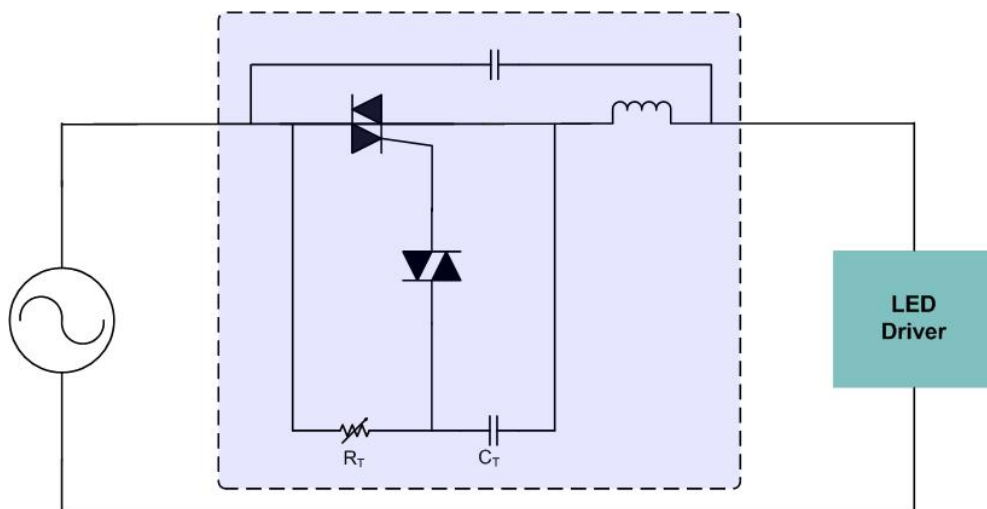


Figure 6. Simplified Triac Dimmer Schematic

An electronic driver with similar input capacitance would respond with erratic behavior perceived as flicker or flashing of the LEDs. Elevated currents in this mode of operation can overstress components causing permanent damage to the LED driver. As illustrated, one critical requirement for triac dimming is that the EMI filter has minimal input capacitance and that capacitance should be decoupled from the impedance of the triac and wiring.

Introducing some resistance in the resonant circuit will in principle dampen the oscillations and restore more desirable operation. Critical dampening is achieved by following the formula where L and C represent total inductance and capacitance presented to the dimmer module:

$$R = \sqrt{L/C} \quad (\text{eq. 2})$$

Critical damping is not necessarily required and the complex design of the input filter makes applying this formula difficult. Moreover some dimmers have built in filter inductors as shown in the diagram above and given that the value of the inductor can vary by dimmer manufacturer and design, there are certain dimmers which may have different interactions with the LED driver. As a result, empirical testing with standard mainstream dimmers is required to assure proper operation. That notwithstanding, a starting point can be found by making a few assumptions and substituting in some equivalent values to start the EMI filter design with the basic topology illustrated in Figure 7.

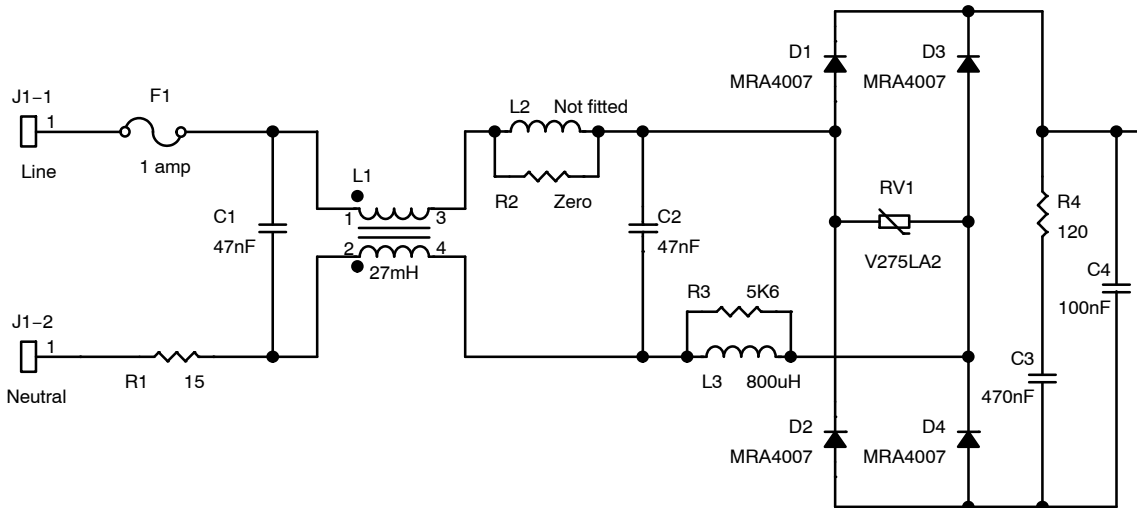


Figure 7. General EMI Filter Topology

C1 appears as a short circuit across the AC line when the triac in the dimmer turns on. As demonstrated in the example above this capacitor should be eliminated or made as low as possible to avoid the initial surge current and still meet EMI filtering requirements. 230 V dimming applications typically work better if C1 is eliminated. 115 V applications can tolerate a small capacitance due to the lower voltage step and less resultant energy storage therefore C1 remains 47 nF. Nevertheless to minimize input surge, this capacitor can be eliminated although this will require additional components in the EMI filter to achieve the appropriate filtering.

R1 limits the peak surge current from the triac turn on and provides some decoupling for C1 to dampen high frequency ringing. As a series element, R1 will dissipate energy following line current squared times resistance. The selection of the value of R1 represents a balance between dampening and power loss. Empirical testing shows R1 = 15 Ω performs well in a 115 Vac input 12 W LED application.

In 230 Vac applications additional resistance is required to compensate for the higher instantaneous voltage switched by the triac. Doubling the voltage requires about four times the resistance compared to the 115 Vac case. Dividing the

resistance in two elements reduces the peak voltage and power stress on the resistor. R1 is therefore selected as 33 Ω and F1 is replaced with 33 Ω. Fusible resistors are used providing limiting protection.

EMI tests for the 115 Vac dimmable solution showed the differential filtering can be reduced compared to the non triac dimmable full range 90–305 Vac solution. L2 was eliminated and L3 reduced to 800 μH.

The dimming function reduces output power as line voltage is reduced. The 230 V dimming application draws much less current at lower line voltage and therefore does not require the same differential filtering as the full range 90 V to 305 V solution. EMI testing revealed L2 and L3 can be reduced to 470 μH.

Energy stored in the filter inductors and in the inductance of the building wiring reacts with the effective capacitance across the line forming a resonant circuit which is excited by the triac turning on. After an initial peak, the resonant behavior of the line current forms a negative peak before dampening out. This resonant signature is superimposed on the generally sinusoidal shape of the operating line current. Should this negative peak fall below the triac holding current, the triac will commutate off stopping the flow of current. The dimmer circuitry will recharge the internal

timer and again issue a gate pulse to the triac. If the triac fires more than one time per half cycle, this could result in flicker. As shown below, if the hold current falls below zero and reverses the triac turns off and multiple firings will occur.

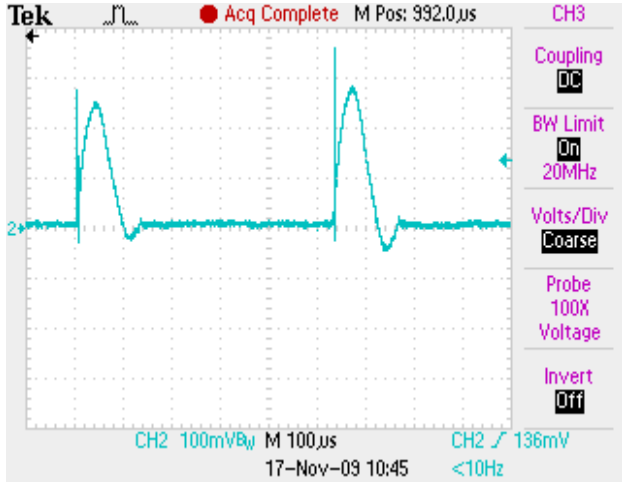


Figure 8. Input Current Waveform Illustrating Multiple Firing Events

Breaking this cycle requires keeping the triac current above the holding threshold. A preload or dampening resistor could be added across the AC line, but would result in significant dissipation.

The frequency of the resonance is relatively high compared to the applied input power frequency. If a capacitor is placed in series with the dampening resistor the lower power line frequency will be blocked but the higher frequency associated with the resonance will allow effective operation of the dampening resistor while limiting dissipation associated with the input power frequency. In practice, this blocking capacitor should be about two to five times the value of C4. Empirical testing shows at this power level blocking capacitor C3 of 470 nF and dampening resistor R4 of 120 Ω works well for 115 V ac dimmer applications. 230 V applications work well with R4 at 470 Ω and C3 at 220 nF.

Optimizing Bias Power for Dimming

Low conduction angles reduce the peak voltage presented to the LED driver. The bias network must be able to provide power even during these short low amplitude periods. Capacitor C6 peak charges during conduction time storing sufficient energy to power the bias regulator until the next cycle of triac dimming. Since the dimmer position is unknown at startup, the circuit was designed to startup with an equivalent AC input of 30 Vac. Normal startup when the dimmer is at the maximum position is less than 500 ms, this will increase if the dimmer is in a lower position.

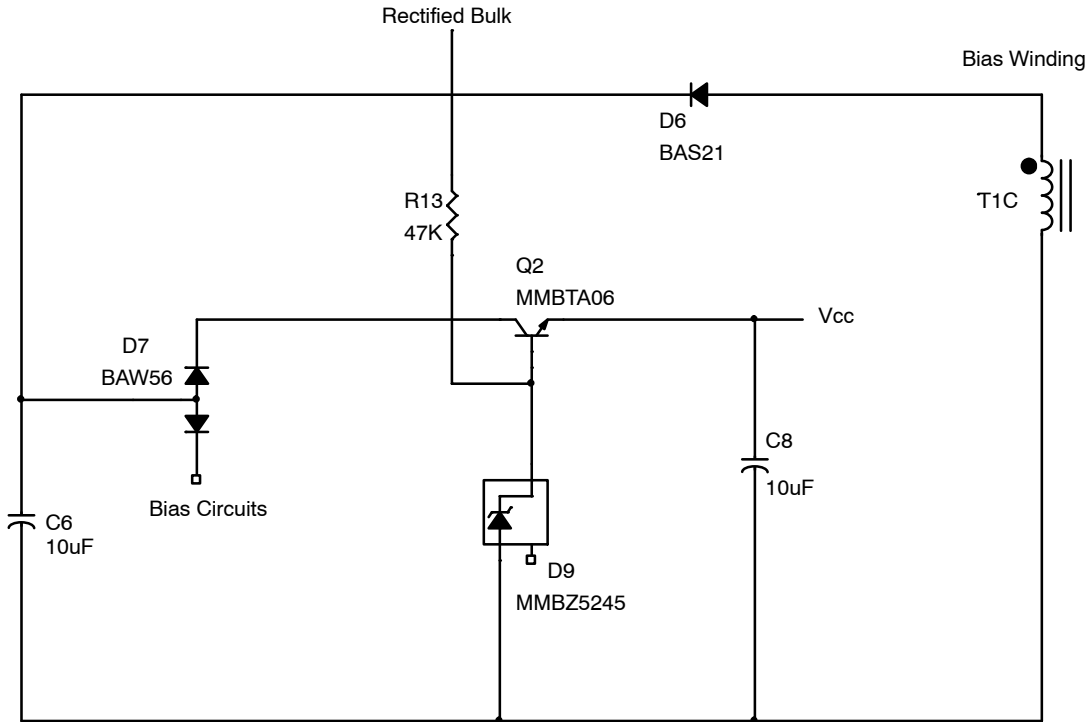
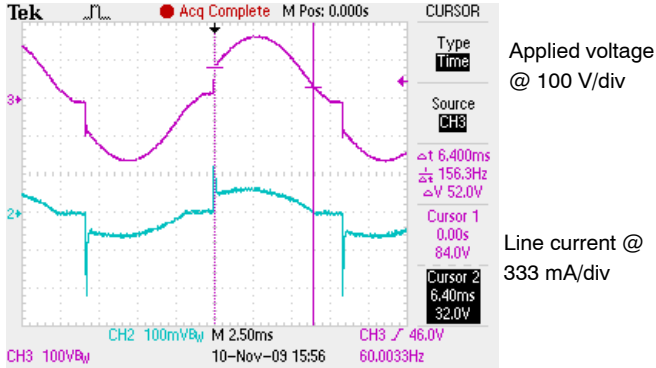


Figure 9. Detail of Primary Biasing Network

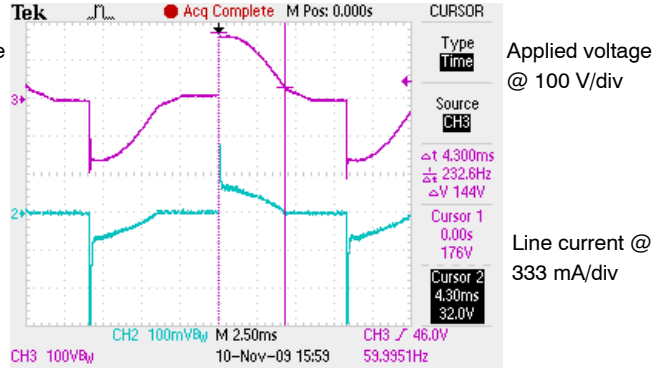
Performance with Triac Dimmer

The demonstration board was tested with 115 V ac 60 Hz applied to a triac dimmer. The load was 12 LEDs operating at 350 mA. The images below show input line voltage and

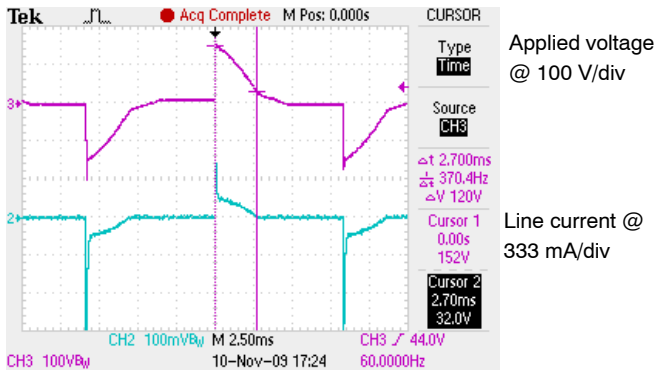
current waveforms from a triac dimmer powering the LED demonstration board. Note the wave shape as the conduction angle is changed.



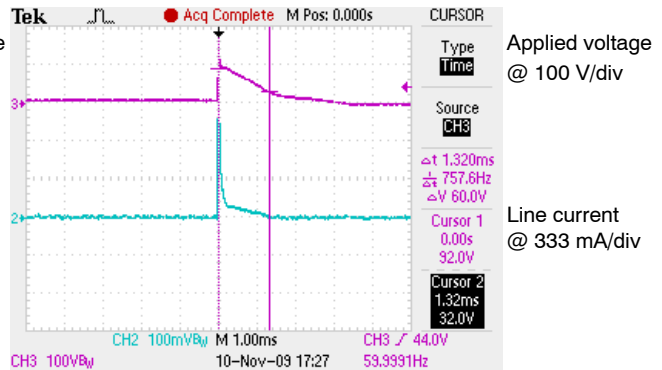
- Dimmer conduction angle: 138°
- Measured input to demo board: 112.8 Vrms
- LED current: 349 mA



- Dimmer conduction angle: 93°
- Measured input to demo board: 91.8 Vrms
- LED current: 246 mA



- Dimmer conduction angle: 58°
- Measured input to demo board: 60.7 Vrms
- LED current: 105 mA



- Dimmer conduction angle: 28.5°
- Measured input to demo board: 27.5 Vrms
- LED current: 17 mA

Figure 10. Input Characteristics with Various Dimmer Conduction Angles

Figure 11 below demonstrates the effect of limiting the maximum on-time of the LED demonstration board set for operation with a 12 W LED load. Note the LED current diminishes as the input line voltage is reduced. The reduction in LED current is fairly linear with line voltage.

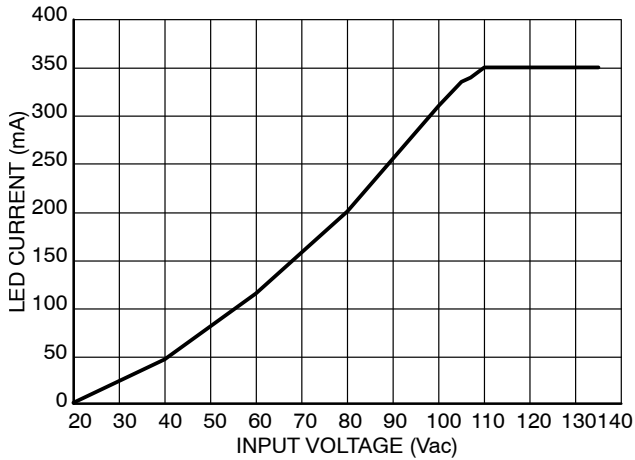


Figure 11. Line Regulation of Demo Board Set for 115 Vac and 12 W Load

Factors to Consider with Phase Cut Dimmers

Many manufacturers produce dimmers and each model is slightly different. As previously mentioned, most dimmers are rated for 40 to 60 W minimum and some may not perform well with a lower power LED fixture. The issue at hand is the line current must be greater than the triac holding current. There is little which can be done about this situation short of adding a preload but it is fairly common to have multiple lights on the same dimmer so this is normally not a problem. In a new build, a proper dimmer can be selected up front, but in some cases especially if there was only a single LED load on the dimmer circuit it would be necessary to update the dimmer to a more appropriate model. In our dimmer compatibility testing, there are a wide range of commercial dimmers which work with one 12 W LED load.

Standard phase cut dimmers require a small amount of energy from the power line for internal biasing. A typical two-wire dimmer must extract this energy by utilizing a small amount of the available conduction angle making it unavailable to pass on to the load. As such the maximum conduction angle is typically limited to 120 – 160°.

Minimum conduction angle varies widely from one dimmer model to another. Again, this is a characteristic of the dimmer design. The NCL30000 controller solution can utilize the full range of dimmer conduction angle. Some variation in minimum LED current is seen depending on the dimmer model used. This is illustrated in Figure 12 for a range of dimmers.

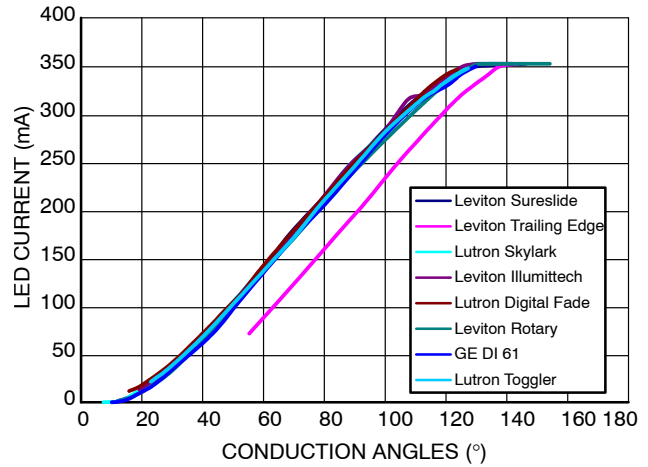


Figure 12. Performance of Various 115 V Dimmer Modules with 12 W Load

Trailing edge dimmers behave somewhat differently than leading edge models as shown in Figure 12. Note the trailing edge response shown in pink begins reducing LED current at a higher conduction angle than the leading edge devices but follows the same shape characteristic. This trailing edge dimmer displays a reduced range of maximum and minimum conduction angles.

Sophisticated dimmer modules with digital control are now widely available. These dimmers provide features like slow fade on and fade off, delayed off providing light while a person leaves a room, or even motion-sensing occupancy sensors. Many of these special feature dimmers require additional bias power and therefore may limit the maximum and/or minimum conduction angle. This will of course affect the current range delivered to the LED load. Some of the advanced dimmers require a neutral wire connection. In this case, a wider conduction angle range is usually available.

Comments on Trailing Edge (Electronic Dimmers)

Electronic or trailing edge dimmers typically do not display the problems associated with triac or leading edge dimmers. Trailing edge dimmers do not apply the high amplitude step voltage to the EMI filter and consequently do not stimulate the resonant current waveform. The dimming characteristic is somewhat different from their triac dimmer counterparts and often displays a narrower range of conduction angle control.

Unlike some dimmable LED drivers available, the NCL30000 does not differentiate between leading and trailing edge control. No special circuits are required to provide compatibility with trailing edge dimmers. The dimming function is based on the RMS level of the input voltage whether the cut in phase occurs at the beginning or end of the input waveform.

Acoustic Considerations

Triac dimming creates a current step each half cycle of the input waveform. The rapidly rising current develops a corresponding magnetic field in the EMI filter magnetic devices resulting in magnetostriction or small movements. This movement generates audible noise as a series of pulses at twice the line frequency. Multi-piece cores are particularly susceptible to this magnetic effect and can emit detectable audible noise. The wire windings themselves also move slightly adding to problem. Encapsulating or potting the core and windings suppresses audible noise.

Inductors utilizing open magnetic path cores introduce additional challenges. High peak currents through the inductor create strong and rapidly changing magnetic fields. Adjacent magnetic devices or nearby ferrous materials can react to the changing fields supporting magnetic force between devices. The alternating force may cause the circuit board to flex emitting high sound levels. If open magnetic path inductors are used the effects of magnetic coupling can be minimized by increasing the distance between components.

Empirical testing shows powdered iron toroidal inductors emit significantly less audible noise than

drum-type inductors. Other geometries or winding processes may also prove effective at reducing noise. Triac dimmable drivers should be evaluated in quiet surroundings and in their enclosure to assess the acoustic performance.

The flyback transformer may also emit noise when used with a dimmer. The typical two piece core and winding configuration can exacerbate emanations. Minimizing gaps or soft insulating materials in the windings and varnishing the transformer assembly helps suppress audible noise.

Conclusion

The NCL30000 Power Factor Corrected LED Driver is a versatile controller solution for many applications. A high power factor single stage isolated LED driver based on this device can be controlled by conventional line dimmers. This driver provides smooth dimming function with triac leading-edge or electronic trailing-edge dimmers. The design process presented ensures wide dimming range matched to LED load characteristics.

For details on setting operating parameters for each reference design please refer to the Demo Board Manuals for the NCL30000LED1GEVB and NCL30000LED2GEVB.

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