

# LM3445

## Triac Dimmable Offline LED Driver

### General Description

The LM3445 is an adaptive constant off-time AC/DC buck (step-down) constant current controller designed to be compatible with triac dimmers. The LM3445 provides a constant current for illuminating high power LEDs and includes a triac dim decoder. The dim decoder allows wide range LED dimming using standard triac dimmers. The high frequency capable architecture allows the use of small external passive components. The LM3445 includes a bleeder circuit to ensure proper triac operation by allowing current flow while the line voltage is low to enable proper firing of the triac. A passive PFC circuit ensures good power factor by drawing current directly from the line for most of the cycle, and provides a constant positive voltage to the buck regulator. Additional features include thermal shutdown, current limit and  $V_{CC}$  under-voltage lockout.

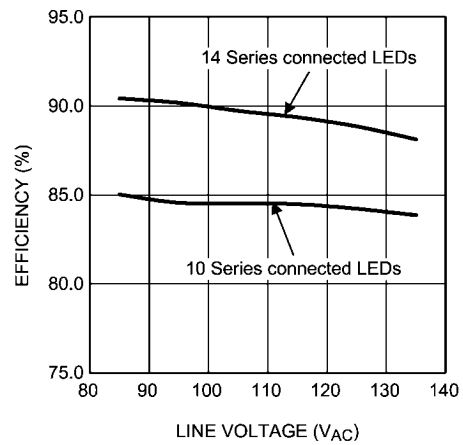
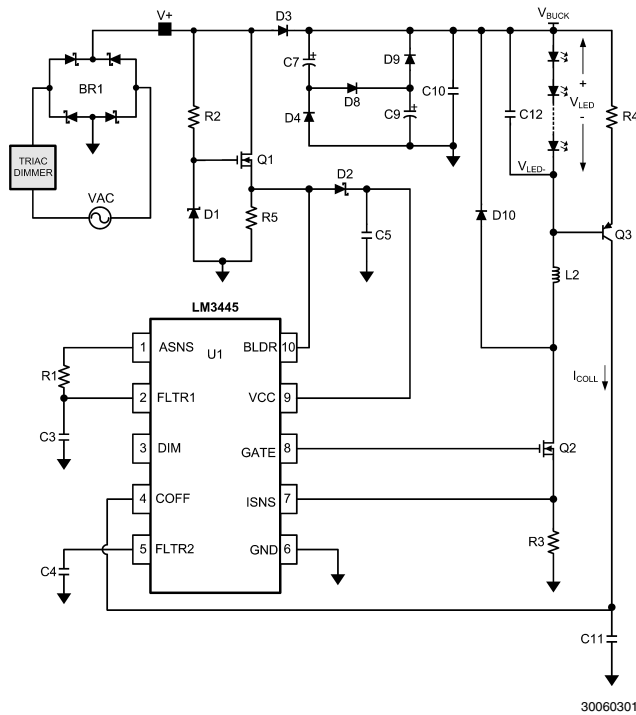
### Features

- Triac dim decoder circuit for LED dimming
- Application voltage range  $80V_{AC} - 270V_{AC}$
- Capable of controlling LED currents greater than 1A
- Adjustable switching frequency
- Low quiescent current
- Adaptive programmable off-time allows for constant ripple current
- Thermal shutdown
- No 120Hz flicker
- Low profile 10 pin MSOP Package
- Patent pending drive architecture

### Applications

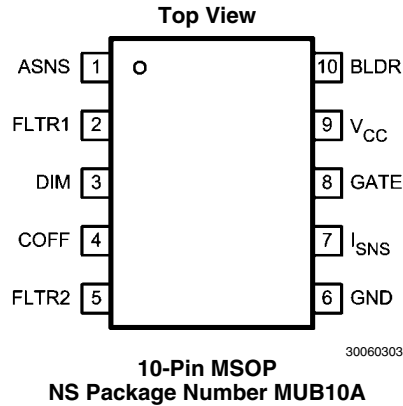
- Retro Fit Triac Dimming
- Solid State Lighting
- Industrial and Commercial Lighting
- Residential Lighting

### Typical LM3445 LED Driver Application Circuit



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## Connection Diagram



## Ordering Information

Order Number	Spec.	Package Type	NSC Package Drawing	Top Mark	Supplied As
LM3445MM	NOPB	MSOP-10	MUB10A	SULB	1000 Units, Tape and Reel
LM3445MMX	NOPB	MSOP-10	MUB10A	SULB	3500 Units, Tape and Reel

## Pin Descriptions

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 <sub>CC</sub>	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.

## Absolute Maximum Ratings (Note 1, Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

BLDR to GND	-0.3V to +17V
V <sub>CC</sub> , GATE, FLTR1 to GND	-0.3V to +14V
ISNS to GND	-0.3V to +2.5V
ASNS, DIM, FLTR2, COFF to GND	-0.3V to +7.0V
COFF Input Current	100mA
Continuous Power Dissipation	Internally Limited <small>(Note 3)</small>

ESD Susceptibility HBM <small>(Note 4)</small>	2 kV
Junction Temperature (T <sub>J-MAX</sub> )	150°C
Storage Temperature Range Maximum Lead Temp. Range (Soldering)	-65°C to +150°C 260°C

## Operating Conditions

V <sub>CC</sub>	8.0V to 12V
Junction Temperature	-40°C to +125°C

**Electrical Characteristics** Limits in standard type face are for T<sub>J</sub> = 25°C and those with **boldface type** apply over the full **Operating Temperature Range** (T<sub>J</sub> = -40°C to +125°C). Minimum and Maximum limits are guaranteed through test, design, or statistical correlation. Typical values represent the most likely parametric norm at T<sub>J</sub> = +25°C, and are provided for reference purposes only.

Symbol	Parameter	Conditions	Min	Typ	Max	Units
<b>BLEEDER</b>						
R <sub>BLDR</sub>	Bleeder resistance to GND	I <sub>BLDR</sub> = 10mA		230	<b>325</b>	Ω
<b>V<sub>CC</sub> SUPPLY</b>						
I <sub>VCC</sub>	Operating supply current			2.00	<b>2.85</b>	mA
V <sub>CC-UVLO</sub>	Rising threshold			7.4	<b>7.7</b>	V
	Falling threshold		<b>6.0</b>	6.4		
	Hysteresis			1		
<b>COFF</b>						
V <sub>COFF</sub>	Time out threshold		<b>1.225</b>	1.276	<b>1.327</b>	V
R <sub>COFF</sub>	Off timer sinking impedance			33	<b>60</b>	Ω
t <sub>COFF</sub>	Restart timer			180		μs
<b>CURRENT LIMIT</b>						
V <sub>ISNS</sub>	ISNS limit threshold		<b>1.174</b>	1.269	<b>1.364</b>	V
t <sub>ISNS</sub>	Leading edge blanking time			125		ns
	Current limit reset delay			180		μs
	ISNS limit to GATE delay	ISNS = 0 to 1.75V step		33		ns
<b>INTERNAL PWM RAMP</b>						
f <sub>RAMP</sub>	Frequency			5.85		kHz
V <sub>RAMP</sub>	Valley voltage		<b>0.96</b>	1.00	<b>1.04</b>	V
	Peak voltage		<b>2.85</b>	3.00	<b>3.08</b>	
D <sub>RAMP</sub>	Maximum duty cycle		<b>96.5</b>	98.0		%
<b>DIM DECODER</b>						
t <sub>ANG_DET</sub>	Angle detect rising threshold	Observed on BLDR pin	<b>6.79</b>	7.21	<b>7.81</b>	V
V <sub>ASNS</sub>	ASNS filter delay			4		μs
	ASNS VMAX		<b>3.85</b>	4.00	<b>4.15</b>	V
I <sub>ASNS</sub>	ASNS drive capability sink	V <sub>ASNS</sub> = 2V		7.6		mA
	ASNS drive capability source	V <sub>ASNS</sub> = 2V		-4.3		
	DIM low sink current	V <sub>DIM</sub> = 1V	<b>1.65</b>	2.80		
	DIM High source current	V <sub>DIM</sub> = 4V		-4.00	<b>-3.00</b>	
V <sub>DIM</sub>	DIM low voltage	PWM input voltage threshold	<b>0.9</b>	1.33		V
	DIM high voltage			2.33	<b>3.15</b>	
V <sub>TSTH</sub>	Tri-state threshold voltage	Apply to FLTR1 pin		4.87	<b>5.25</b>	V

Symbol	Parameter	Conditions	Min	Typ	Max	Units
$R_{DIM}$	DIM comparator tri-state impedance		10			M $\Omega$
<b>CURRENT SENSE COMPARATOR</b>						
$V_{FLTR2}$	FLTR2 open circuit voltage		720	750	780	mV
$R_{FLTR2}$	FLTR2 impedance			420		k $\Omega$
$V_{OS}$	Current sense comparator offset voltage		-4.0	0.1	4.0	mV
<b>GATE DRIVE OUTPUT</b>						
$V_{DRVH}$	GATE high saturation	$I_{GATE} = 50 \text{ mA}$		0.24	0.50	V
$V_{DRVL}$	GATE low saturation	$I_{GATE} = 100 \text{ mA}$		0.22	0.50	
$I_{DRV}$	Peak source current	$GATE = V_{CC}/2$		-0.77		A
	Peak sink current	$GATE = V_{CC}/2$		0.88		
$t_{DV}$	Rise time	$C_{load} = 1 \text{ nF}$		15		ns
	Fall time	$C_{load} = 1 \text{ nF}$		15		
<b>THERMAL SHUTDOWN</b>						
$T_{SD}$	Thermal shutdown temperature	(Note 5)		165		$^{\circ}\text{C}$
	Thermal shutdown hysteresis			20		
<b>THERMAL SHUTDOWN</b>						
$R_{\theta JA}$	MSOP-10 junction to ambient			121		$^{\circ}\text{C}/\text{W}$

**Note 1:** Absolute maximum ratings are limits beyond which damage to the device may occur. Operating Ratings are conditions for which the device is intended to be functional, but device parameter specifications may not be guaranteed. For guaranteed specifications and test conditions, see the Electrical Characteristics.

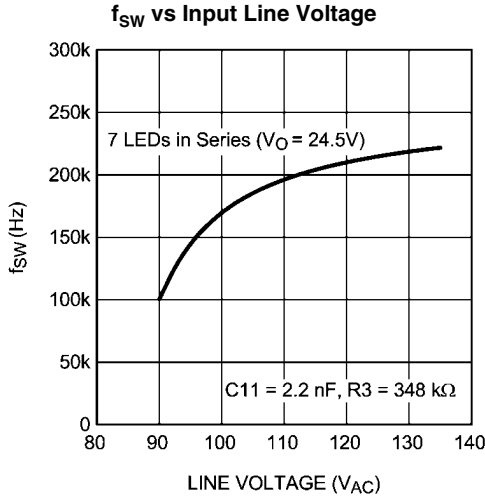
**Note 2:** All voltages are with respect to the potential at the GND pin, unless otherwise specified.

**Note 3:** Internal thermal shutdown circuitry protects the device from permanent damage. Thermal shutdown engages at  $T_J = 165^{\circ}\text{C}$  (typ.) and disengages at  $T_J = 145^{\circ}\text{C}$  (typ).

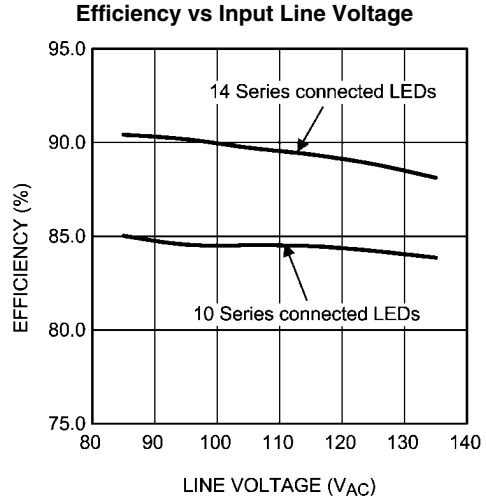
**Note 4:** Human Body Model, applicable std. JESD22-A114-C.

**Note 5:** Junction-to-ambient thermal resistance is highly application and board-layout dependent. In applications where high maximum power dissipation exists, special care must be paid to thermal dissipation issues in board design. In applications where high power dissipation and/or poor package thermal resistance is present, the maximum ambient temperature may have to be derated. Maximum ambient temperature ( $T_{A-MAX}$ ) is dependent on the maximum operating junction temperature ( $T_{J-MAX-OP} = 125^{\circ}\text{C}$ ), the maximum power dissipation of the device in the application ( $P_{D-MAX}$ ), and the junction-to ambient thermal resistance of the part/package in the application ( $R_{\theta JA}$ ), as given by the following equation:  $T_{A-MAX} = T_{J-MAX-OP} - (R_{\theta JA} \times P_{D-MAX})$ .

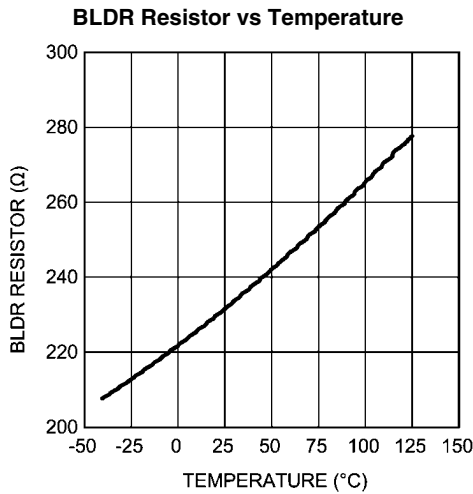
# Typical Performance Characteristics



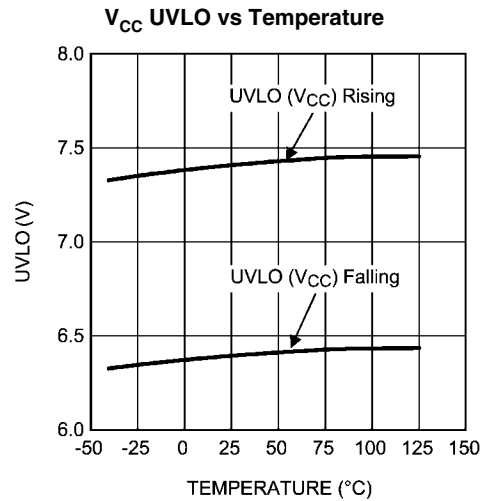
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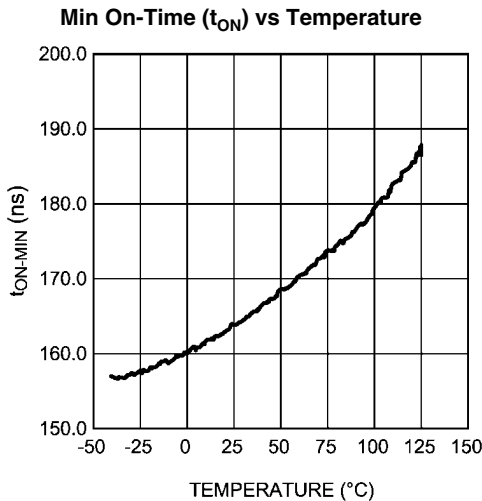
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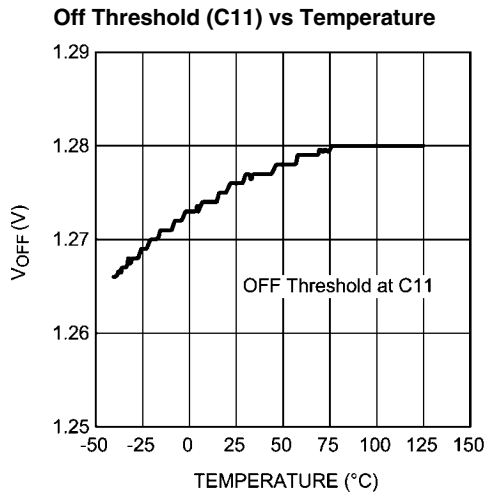
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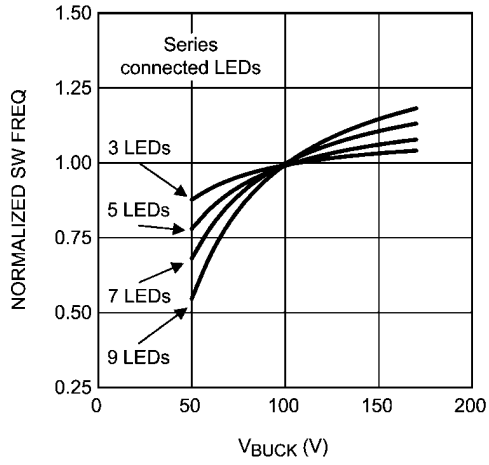


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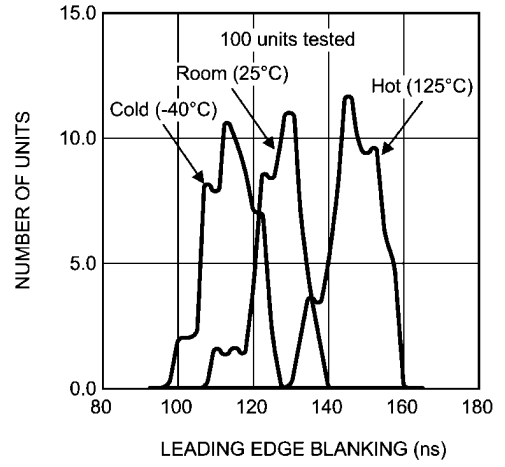
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Normalized Variation in  $f_{SW}$  over  $V_{BUCK}$  Voltage



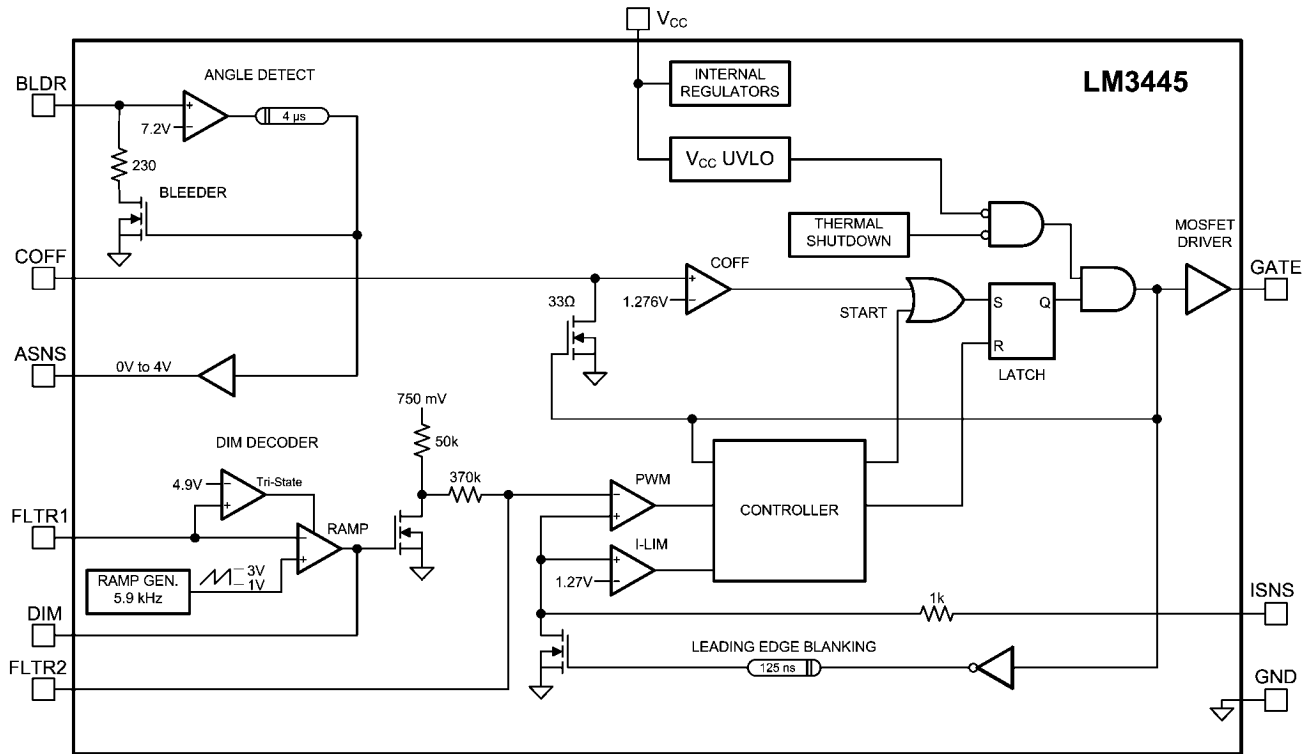
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Leading Edge Blanking Variation Over Temperature



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# Simplified Internal Block Diagram



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FIGURE 1. Simplified Block Diagram

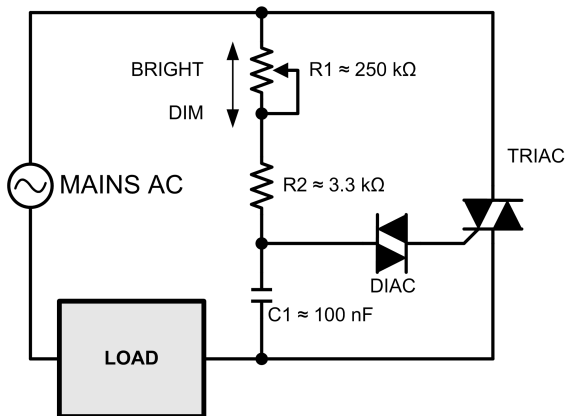
## Application Information

### FUNCTIONAL DESCRIPTION

The LM3445 contains all the necessary circuitry to build a line-powered (mains powered) constant current LED driver whose output current can be controlled with a conventional triac dimmer.

### OVERVIEW OF PHASE CONTROL DIMMING

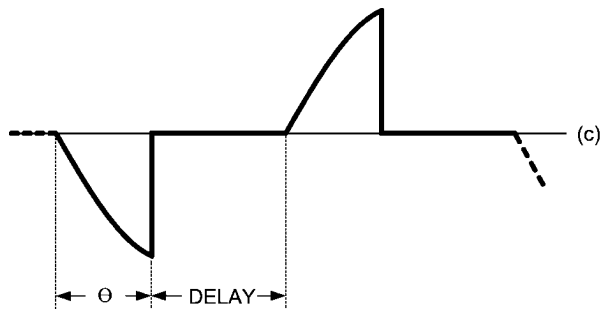
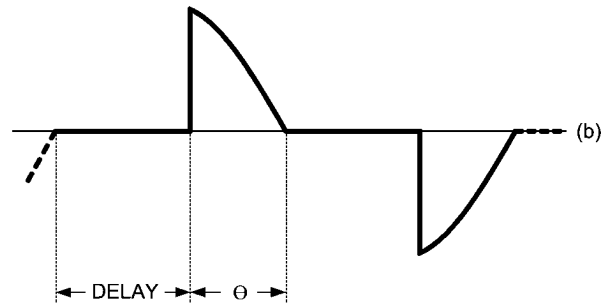
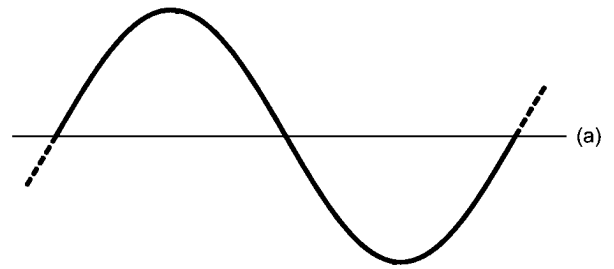
A basic "phase controlled" triac dimmer circuit is shown in Figure 2.



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**FIGURE 2. Basic Triac Dimmer**

An RC network consisting of R1, R2, and C1 delay the turn on of the triac until the voltage on C1 reaches the trigger voltage of the diac. Increasing the resistance of the potentiometer (wiper moving downward) increases the turn-on delay which decreases the on-time or "conduction angle" of the triac ( $\theta$ ). This reduces the average power delivered to the load. Voltage waveforms for a simple triac dimmer are shown in Figure 3. Figure 3a shows the full sinusoid of the input voltage. Even when set to full brightness, few dimmers will provide 100% on-time, i.e., the full sinusoid.



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**FIGURE 3. Line Voltage and Dimming Waveforms**

Figure 3b shows a theoretical waveform from a dimmer. The on-time is often referred to as the "conduction angle" and may be stated in degrees or radians. The off-time represents the delay caused by the RC circuit feeding the triac. The off-time be referred to as the "firing angle" and is simply  $180^\circ - \theta$ .

Figure 3c shows a waveform from a so-called reverse phase dimmer, sometimes referred to as an electronic dimmer. These typically are more expensive, microcontroller based dimmers that use switching elements other than triacs. Note that the conduction starts from the zero-crossing, and terminates some time later. This method of control reduces the noise spike at the transition.

Since the LM3445 has been designed to assess the relative on-time and control the LED current accordingly, most phase-control dimmers, both forward and reverse phase, may be used with success.



## Theory of Operation

Refer to figure 4 below which shows the LM3445 along with basic external circuitry.

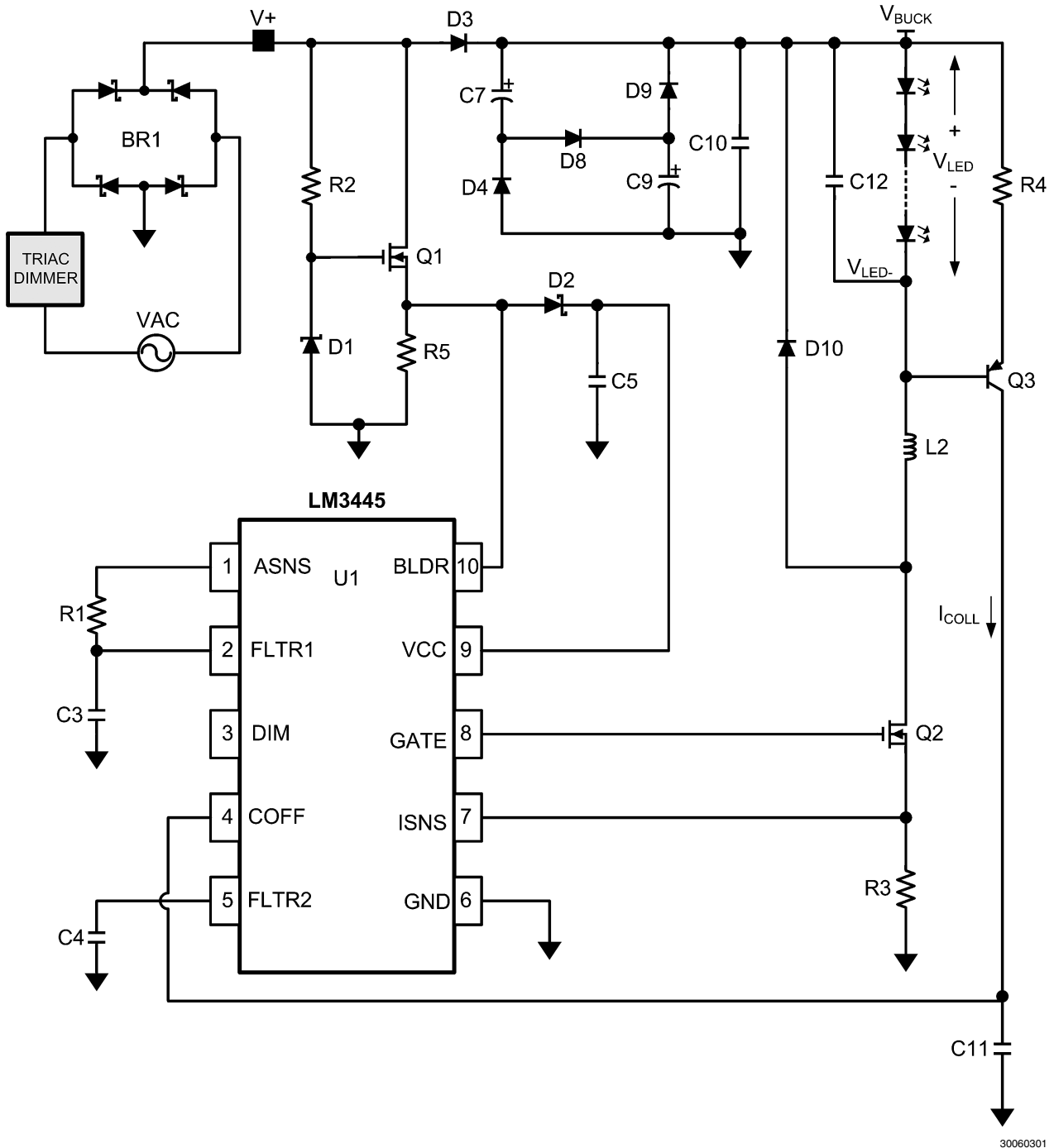
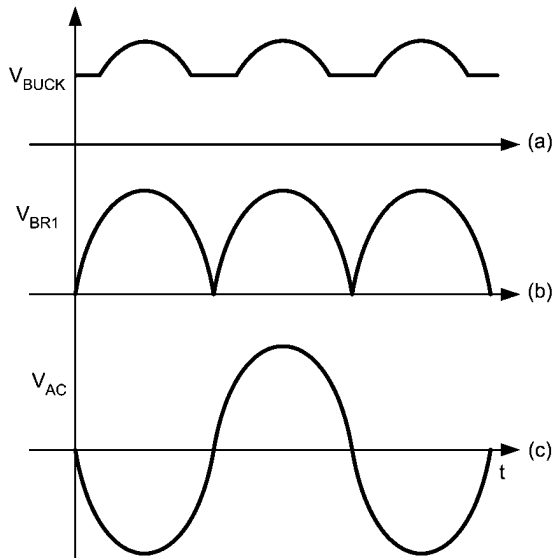


FIGURE 4. LM3445 Schematic

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### SENSING THE RECTIFIED TRIAC WAVEFORM

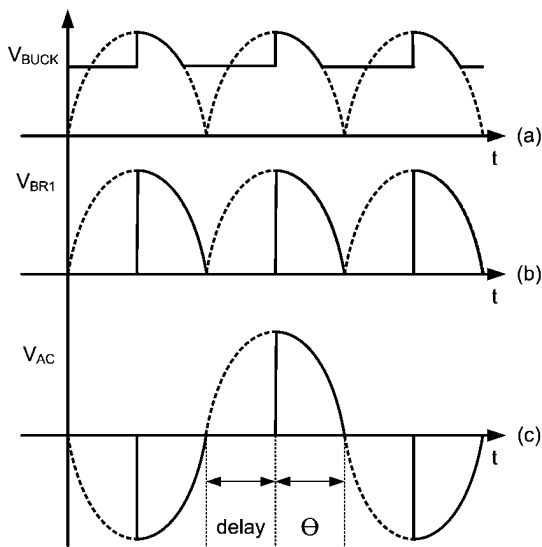
A bridge rectifier, BR1, converts the line (mains) voltage (5c) into a series of half-sines as shown in 5b. Figure 5a shows a typical voltage waveform after diode D3 (valley fill circuit, or  $V_{BUCK}$ ).



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**FIGURE 5. Voltage Waveforms After Bridge Rectifier Without Triac Dimming**

Figure 6c and 6b show typical triac dimmed voltage waveforms before and after the bridge rectifier. Figure 6a shows a typical triac dimmed voltage waveform after diode D3 (valley fill circuit, or  $V_{BUCK}$ ).

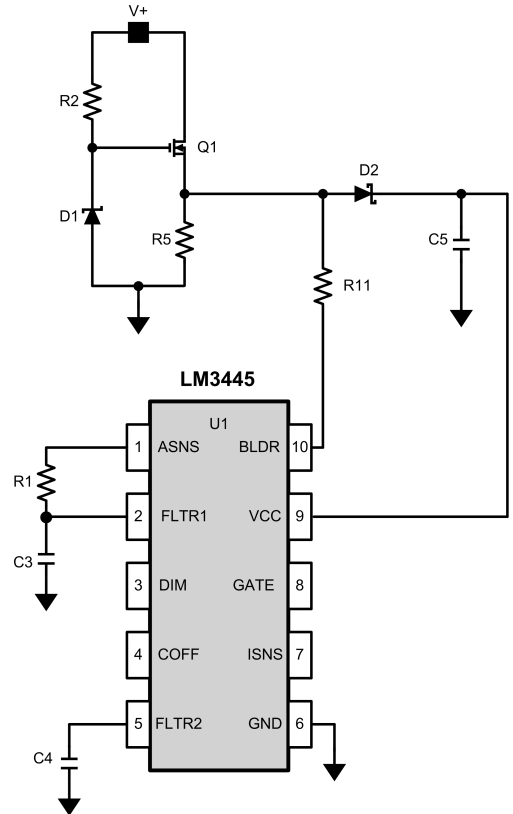


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**FIGURE 6. Voltage Waveforms After Bridge Rectifier With Triac Dimming**

### LM3445 LINE SENSING CIRCUITRY

An external series pass regulator (R2, D1, and Q1) translates the rectified line voltage to a level where it can be sensed by the BLDR pin on the LM3445.



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**FIGURE 7. LM3445 AC Line Sense Circuitry**

D1 is typically a 15V zener diode which forces transistor Q1 to “stand-off” most of the rectified line voltage. Having no capacitance on the source of Q1 allows the voltage on the BLDR pin to rise and fall with the rectified line voltage as the line voltage drops below zener voltage D1 (see the section on Angle Detect).

A diode-capacitor network (D2, C5) is used to maintain the voltage on the VCC pin while the voltage on the BLDR pin goes low. This provides the supply voltage to operate the LM3445.

Resistor R5 is used to bleed charge out of any stray capacitance on the BLDR node and may be used to provide the necessary holding current for the dimmer when operating at light output currents.

### TRIAC HOLDING CURRENT RESISTOR

In order to emulate an incandescent light bulb (essentially a resistor) with any LED driver, the existing triac will require a small amount of holding current throughout the AC line cycle. An external resistor (R5) needs to be placed on the source of Q1 to perform this function. Most existing triac dimmers only require a few milliamps of current to hold them on. A few “less expensive” triacs sold on the market will require a bit more current. The value of resistor R5 will depend on:

- What type of triac the LM3445 will be used with
- How many light fixtures are running off of the triac

With a single LM3445 circuit on a common triac dimmer, a holding current resistor between 3 k $\Omega$  and 5 k $\Omega$  will be required. As the number of LM3445 circuits is added to a single dimmer, the holding resistor R5’s resistance can be increased. A few triac dimmers will require a resistor as low as 1 k $\Omega$  or lower for a single LM3445 circuit. The trade-off will be



The valley-fill circuit allows the buck regulator to draw power throughout a larger portion of the AC line. This allows the capacitance needed at  $V_{\text{BUCK}}$  to be lower than if there were no valley-fill circuit, and adds passive power factor correction (PFC) to the application. Besides better power factor correction, a valley-fill circuit allows the buck converter to operate while separate circuitry translates the dimming information. This allows for dimming that isn't subject to 120Hz flicker that can be perceived by the human eye.

### VALLEY-FILL OPERATION

When the "input line is high", power is derived directly through D3. The term "input line is high" can be explained as follows. The valley-fill circuit charges capacitors C7 and C9 in series (see figure 9) when the input line is high.

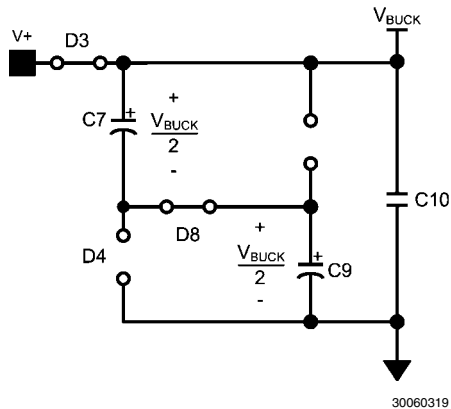


FIGURE 9. Two stage Valley-Fill Circuit when AC Line is High

The peak voltage of a two stage valley-fill capacitor is:

$$V_{\text{VF-CAP}} = \frac{V_{\text{AC-RMS}}\sqrt{2}}{2}$$

As the AC line decreases from its peak value every cycle, there will be a point where the voltage magnitude of the AC line is equal to the voltage that each capacitor is charged. At this point diode D3 becomes reversed biased, and the capacitors are placed in parallel to each other (figure 10), and  $V_{\text{BUCK}}$  equals the capacitor voltage.

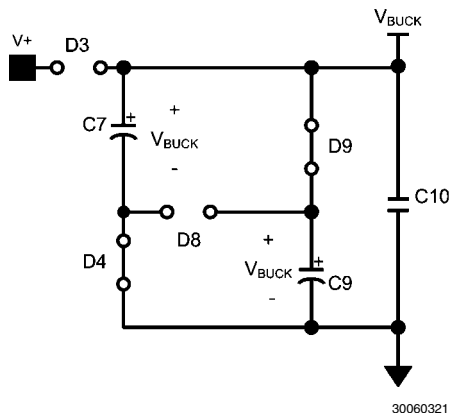


FIGURE 10. Two stage Valley-Fill Circuit when AC Line is Low

A three stage valley-fill circuit performs exactly the same as two-stage valley-fill circuit except now three capacitors are now charged in series, and when the line voltage decreases to:

$$V_{\text{VF-CAP}} = \frac{V_{\text{AC-RMS}}\sqrt{2}}{3}$$

Diode D3 is reversed biased and three capacitors are in parallel to each other.

The valley-fill circuit can be optimized for power factor, voltage hold up and overall application size and cost. The LM3445 will operate with a single stage or a three stage valley-fill circuit as well. Resistor R8 functions as a current limiting resistor during start-up, and during the transition from series to parallel connection. Resistors R6 and R7 are 1 MΩ bleeder resistors, and may or may not be necessary for each application.

### BUCK CONVERTER

The LM3445 is a buck controller that uses a proprietary constant off-time method to maintain constant current through a string of LEDs. While transistor Q2 is on, current ramps up through the inductor and LED string. A resistor R3 senses this current and this voltage is compared to the reference voltage at FLTR2. When this sensed voltage is equal to the reference voltage, transistor Q2 is turned off and diode D10 conducts the current through the inductor and LEDs. Capacitor C12 eliminates most of the ripple current seen in the inductor. Resistor R4, capacitor C11, and transistor Q3 provide a linear current ramp that sets the constant off-time for a given output voltage.

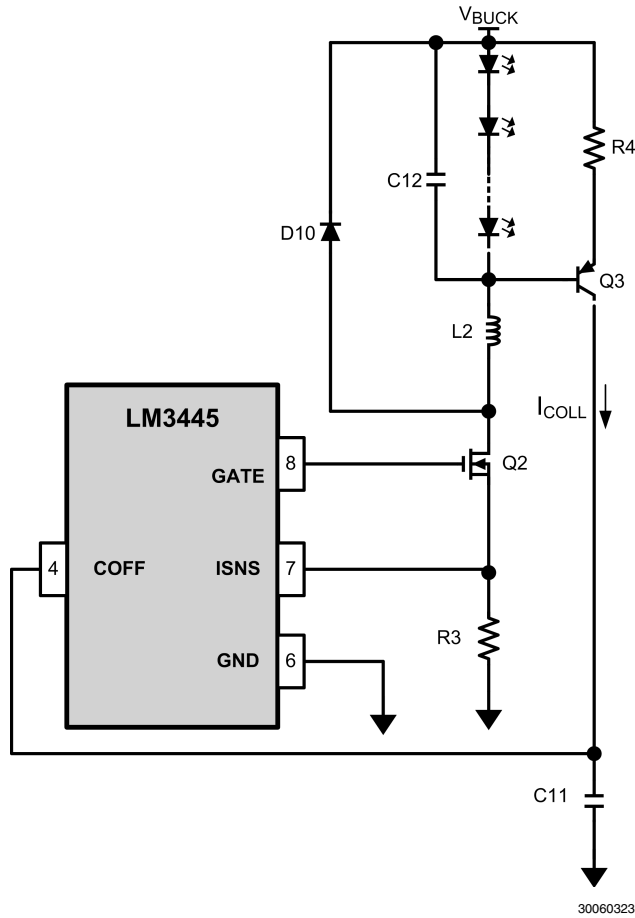


FIGURE 11. LM3445 Buck Regulation Circuit

**OVERVIEW OF CONSTANT OFF-TIME CONTROL**

A buck converter's conversion ratio is defined as:

$$\frac{V_O}{V_{IN}} = D = \frac{t_{ON}}{t_{ON} + t_{OFF}} = t_{ON} \times f_{SW}$$

Constant off-time control architecture operates by simply defining the off-time and allowing the on-time, and therefore the switching frequency, to vary as either  $V_{IN}$  or  $V_O$  changes. The output voltage is equal to the LED string voltage ( $V_{LED}$ ), and should not change significantly for a given application. The input voltage or  $V_{BUCK}$  in this analysis will vary as the input line varies. The length of the on-time is determined by the sensed inductor current through a resistor to a voltage reference at a comparator. During the on-time, denoted by  $t_{ON}$ , MOSFET switch Q2 is on causing the inductor current to increase. During the on-time, current flows from  $V_{BUCK}$ , through the LEDs, through L2, Q2, and finally through R3 to ground. At some point in time, the inductor current reaches a maximum ( $I_{L2-PK}$ ) determined by the voltage sensed at R3 and the ISNS pin. This sensed voltage across R3 is compared

against the voltage of dim decoder output, FLTR2, at which point Q2 is turned off by the controller.

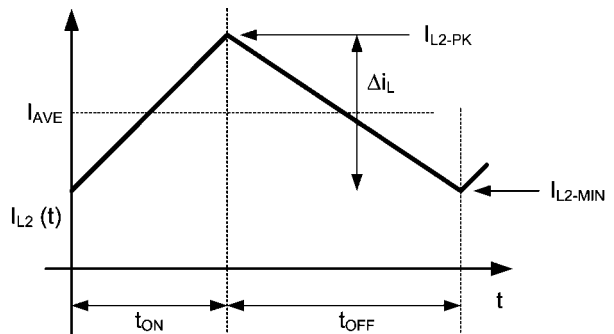


FIGURE 12. Inductor Current Waveform in CCM

During the off-period denoted by  $t_{OFF}$ , the current through L2 continues to flow through the LEDs via D10.

### MASTER/SLAVE OPERATION

Multiple LM3445s can be configured so that large strings of LEDs can be controlled by a single triac dimmer. By doing so, smooth consistent dimming for multiple LED circuits is achieved.

When the FLTR1 pin is tied above 4.9V (typical), preferably to VCC, the ramp comparator is tri-stated, disabling the dim decoder. This allows one or more LM3445 devices or PWM LED driver devices (slaves) to be controlled by a single LM3445 (master) by connecting their DIM pins together.

### MASTER/SLAVE CONFIGURATION

National Semiconductor offers an LM3445 demonstration PCB for customer evaluation through our website. The following description and theory uses reference designators that follow our evaluation PCB. The LM3445 Master/Slave schematics are illustrated below (figures 13 - 15) for clarity. Each board contains a separate circuit for the Master and Slave function. Both the Master and Slave boards will need to be modified from their original stand alone function so that they can be coupled together. Only the Master LM3445 requires use of the Master/Slave circuit for any number of slaves.

### MASTER BOARD MODIFICATIONS

- Remove R10 and replace with a BAS40 diode

- Connect TP18 to TP14 ( $V_{CC}$ )
- Connect TP17 (gate of Q5) to TP15 (gate of Q2)

### SLAVE BOARD(S) MODIFICATIONS

- Remove R11 (disconnects BLDR)
- Tie TP14 (FLTR1) to  $V_{CC}$

### MASTER/SLAVE(S) INTERCONNECTION

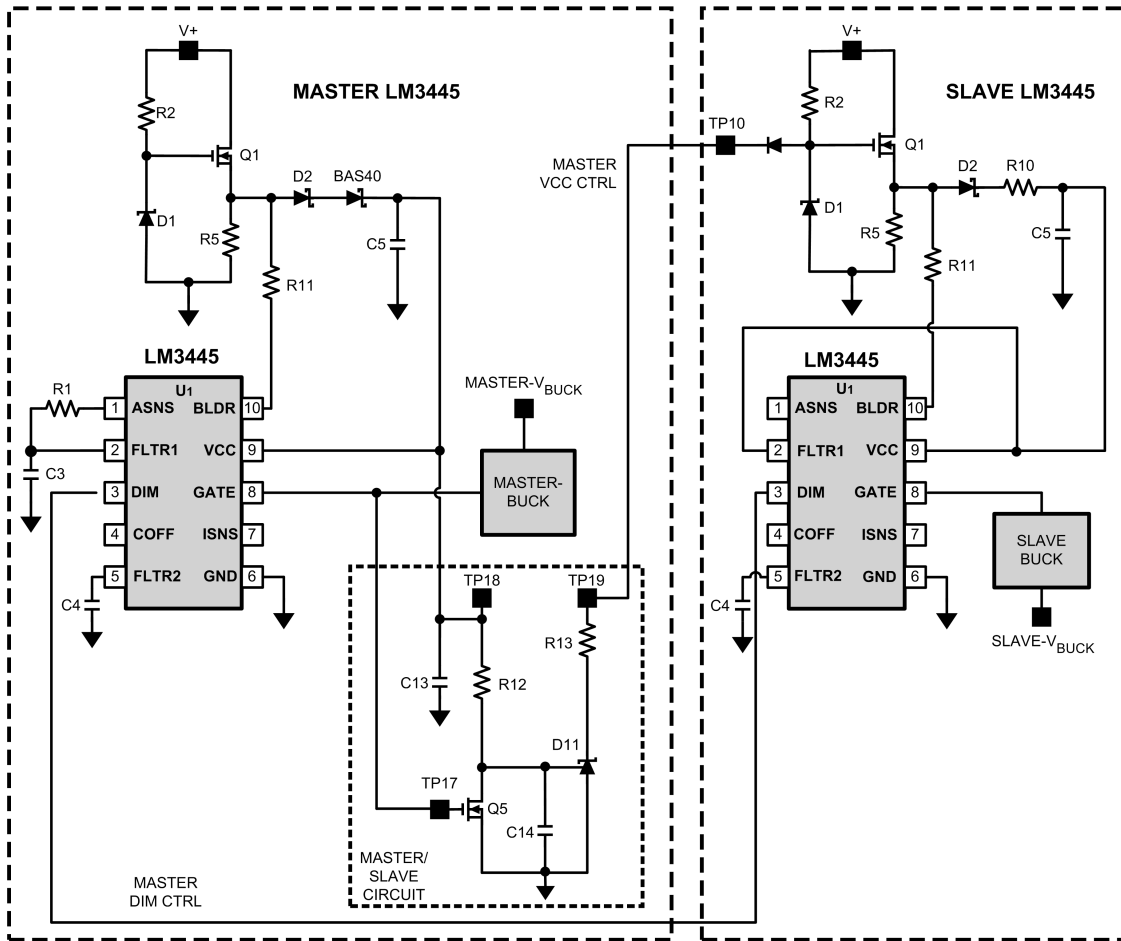
- Connect TP19 of Master to TP10 of Slave (Master VCC Control)
- Connect TP6 (DIM pin) of Master to TP6 (DIM pin) of Slave (Master DIM Control)

### MASTER/SLAVE THEORY OF OPERATION

By placing two series diodes on the Master VCC circuit one forces the master VCC UVLO to become the dominant threshold. When Master VCC drops below UVLO, GATE stops switching and the RC timer ( $>200 \mu s$ ) rises above the TL431 threshold (2.5V) which in turn pulls down on the gate of the Slave pass device (Q1).

The valley-fill circuit could consist of one large circuit to power all LM3445 series connected, or each LM3445 circuit could have a separate valley-fill circuit located near the buck converter.

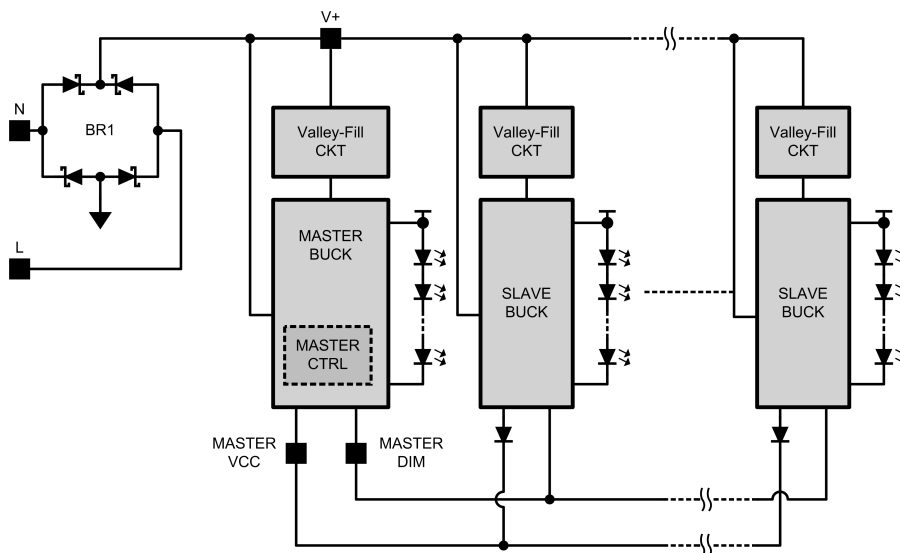
MASTER/SLAVE CONNECTION DIAGRAM



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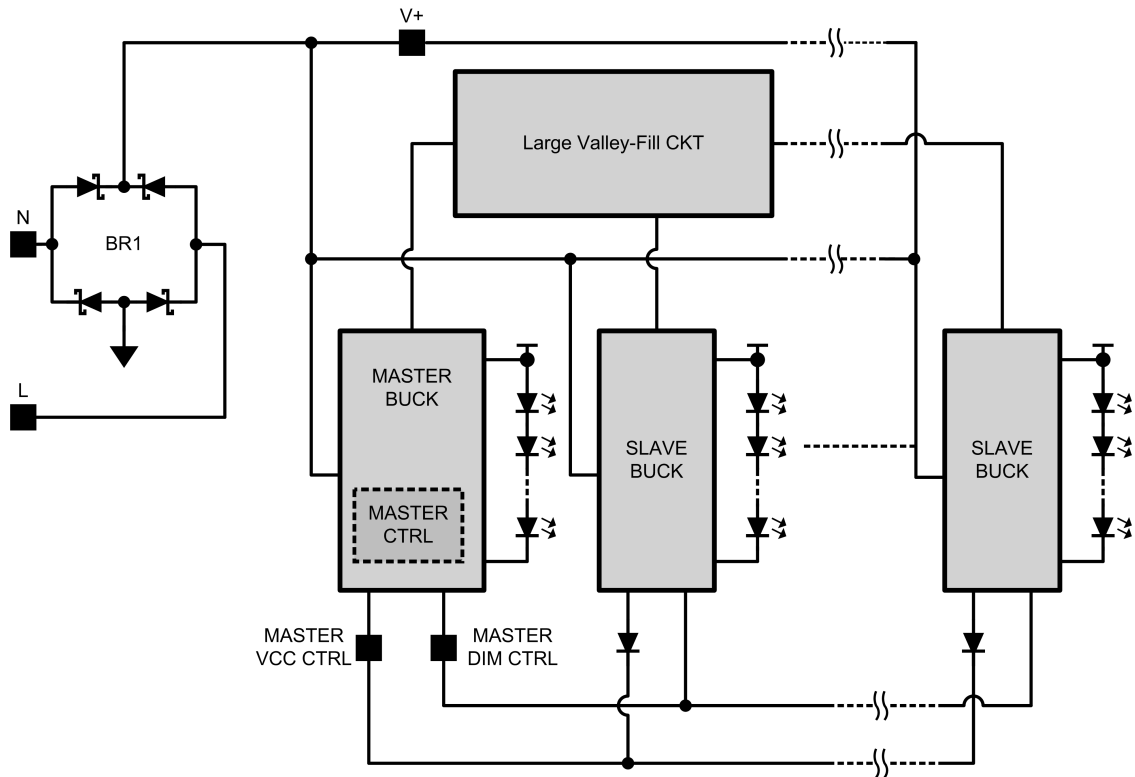
FIGURE 13. Master Slave Configuration

MASTER/SLAVE BLOCK DIAGRAMS



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FIGURE 14. Master/Slave configuration with Separate Valley-Fill Circuits



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**FIGURE 15. Master/Slave configuration with One Valley-Fill Circuit**

#### THERMAL SHUTDOWN

Thermal shutdown limits total power dissipation by turning off the output switch when the IC junction temperature exceeds

165°C. After thermal shutdown occurs, the output switch doesn't turn on until the junction temperature drops to approximately 145°C.



## Design Guide

### DETERMINING DUTY-CYCLE (D)

Duty cycle (D) approximately equals:

$$\frac{V_{LED}}{V_{BUCK}} = D = \frac{t_{ON}}{t_{ON} + t_{OFF}} = t_{ON} \times f_{SW}$$

With efficiency considered:

$$\frac{1}{\eta} \times \frac{V_{LED}}{V_{BUCK}} = D$$

For simplicity, choose efficiency between 75% and 85%.

### CALCULATING OFF-TIME

The “Off-Time” of the LM3445 is set by the user and remains fairly constant as long as the voltage of the LED stack remains constant. Calculating the off-time is the first step in determining the switching frequency of the converter, which is integral in determining some external component values.

PNP transistor Q3, resistor R4, and the LED string voltage define a charging current into capacitor C11. A constant current into a capacitor creates a linear charging characteristic.

$$i = C \frac{dv}{dt}$$

Resistor R4, capacitor C11 and the current through resistor R4 ( $i_{COLL}$ ), which is approximately equal to  $V_{LED}/R4$ , are all fixed. Therefore,  $dv$  is fixed and linear, and  $dt$  ( $t_{OFF}$ ) can now be calculated.

$$t_{OFF} = C11 \times 1.276V \times \left( \frac{R4}{V_{LED}} \right)$$

Common equations for determining duty cycle and switching frequency in any buck converter:

$$f_{SW} = \frac{1}{t_{OFF} + t_{ON}}$$

$$D = \frac{t_{ON}}{t_{ON} + t_{OFF}} = \frac{V_{LED}}{V_{BUCK}}$$

$$D' = \frac{t_{OFF}}{t_{ON} + t_{OFF}}$$

Therefore:

$$f_{SW} = \frac{D}{t_{ON}}, \text{ and } f_{SW} = \frac{1 - D}{t_{OFF}}$$

With efficiency of the buck converter in mind:

$$\frac{V_{LED}}{V_{BUCK}} = \eta \times D$$

Substitute equations and rearrange:

$$f_{SW} = \frac{\left( 1 - \frac{1}{\eta} \times \frac{V_{LED}}{V_{BUCK}} \right)}{t_{OFF}}$$

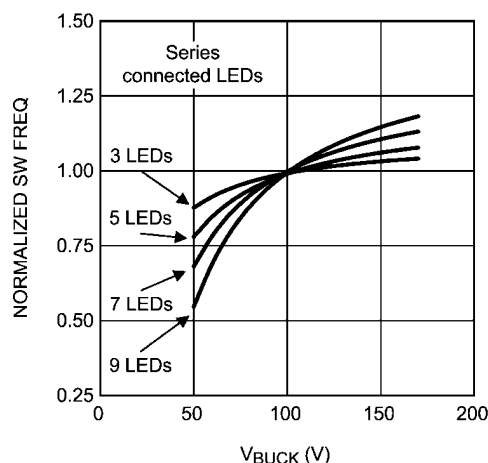
Off-time, and switching frequency can now be calculated using the equations above.

### SETTING THE SWITCHING FREQUENCY

Selecting the switching frequency for nominal operating conditions is based on tradeoffs between efficiency (better at low frequency) and solution size/cost (smaller at high frequency).

The input voltage to the buck converter ( $V_{BUCK}$ ) changes with both line variations and over the course of each half-cycle of the input line voltage. The voltage across the LED string will, however, remain constant, and therefore the off-time remains constant.

The on-time, and therefore the switching frequency, will vary as the  $V_{BUCK}$  voltage changes with line voltage. A good design practice is to choose a desired nominal switching frequency knowing that the switching frequency will decrease as the line voltage drops and increase as the line voltage increases (see figure 16).



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FIGURE 16. Graphical Illustration of Switching Frequency vs  $V_{BUCK}$

The off-time of the LM3445 can be programmed for switching frequencies ranging from 30 kHz to over 1 MHz. A trade-off between efficiency and solution size must be considered when designing the LM3445 application.

The maximum switching frequency attainable is limited only by the minimum on-time requirement (200 ns).

Worst case scenario for minimum on time is when  $V_{BUCK}$  is at its maximum voltage (AC high line) and the LED string voltage ( $V_{LED}$ ) is at its minimum value.

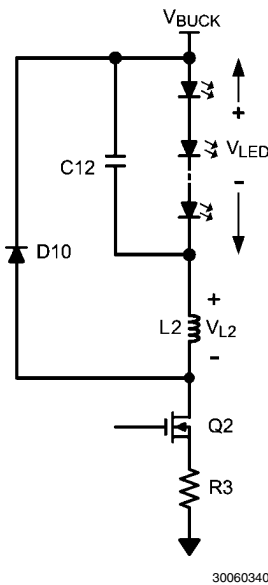
$$t_{ON(MIN)} = \left( \frac{1}{\eta} \times \frac{V_{LED(MIN)}}{V_{BUCK(MAX)}} \right) \frac{1}{f_{SW}}$$

The maximum voltage seen by the Buck Converter is:

$$V_{BUCK(MAX)} = V_{AC-RMS(MAX)} \times \sqrt{2}$$

**INDUCTOR SELECTION**

The controlled off-time architecture of the LM3445 regulates the average current through the inductor (L2), and therefore the LED string current. The input voltage to the buck converter ( $V_{BUCK}$ ) changes with line variations and over the course of each half-cycle of the input line voltage. The voltage across the LED string is relatively constant, and therefore the current through R4 is constant. This current sets the off-time of the converter and therefore the output volt-second product ( $V_{LED} \times \text{off-time}$ ) remains constant. A constant volt-second product makes it possible to keep the ripple through the inductor constant as the voltage at  $V_{BUCK}$  varies.



**FIGURE 17. LM3445 External Components of the Buck Converter**

The equation for an ideal inductor is:

$$v = L \frac{di}{dt}$$

Given a fixed inductor value, L, this equation states that the change in the inductor current over time is proportional to the voltage applied across the inductor.

During the on-time, the voltage applied across the inductor is,

$$V_{L(ON-TIME)} = V_{BUCK} - (V_{LED} + V_{DS(Q2)} + I_{L2} \times R3)$$

Since the voltage across the MOSFET switch (Q2) is relatively small, as is the voltage across sense resistor R3, we can simplify this to approximately,

$$V_{L(ON-TIME)} = V_{BUCK} - V_{LED}$$

During the off-time, the voltage seen by the inductor is approximately:

$$V_{L(OFF-TIME)} = V_{LED}$$

The value of  $V_{L(OFF-TIME)}$  will be relatively constant, because the LED stack voltage will remain constant. If we rewrite the equation for an inductor inserting what we know about the circuit during the off-time, we get:

$$V_{L(OFF-TIME)} = V_{LED} = L \times \frac{\Delta i}{\Delta t}$$

$$V_{L(OFF-TIME)} = V_{LED} = L \times \frac{(I_{(MAX)} - I_{(MIN)})}{\Delta t}$$

Re-arranging this gives:

$$\Delta i \cong t_{OFF} \times \frac{V_{LED}}{L2}$$

From this we can see that the ripple current ( $\Delta i$ ) is proportional to off-time ( $t_{OFF}$ ) multiplied by a voltage which is dominated by  $V_{LED}$  divided by a constant ( $L2$ ).

These equations can be rearranged to calculate the desired value for inductor L2.

$$L2 \cong t_{OFF} \times \frac{V_{LED}}{\Delta i}$$

Where:

$$t_{OFF} = \frac{\left( 1 - \frac{1}{\eta} \times \frac{V_{LED}}{V_{BUCK}} \right)}{f_{SW}}$$

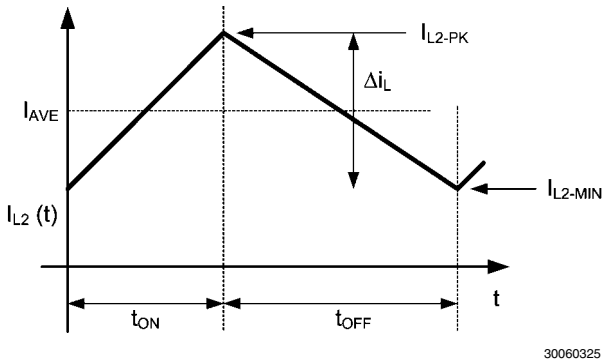
Finally:

$$L2 = \frac{V_{LED} \left( 1 - \frac{1}{\eta} \times \frac{V_{LED}}{V_{BUCK}} \right)}{f_{SW} \times \Delta i}$$

Refer to "Design Example" section of the datasheet to better understand the design process.

## SETTING THE LED CURRENT

The LM3445 constant off-time control loop regulates the peak inductor current ( $I_{L2}$ ). The average inductor current equals the average LED current ( $I_{AVE}$ ). Therefore the average LED current is regulated by regulating the peak inductor current.



**FIGURE 18. Inductor Current Waveform in CCM**

Knowing the desired average LED current,  $I_{AVE}$  and the nominal inductor current ripple,  $\Delta i_L$ , the peak current for an application running in continuous conduction mode (CCM) is defined as follows:

$$I_{L2-PK} = I_{AVE} + \frac{\Delta i_L}{2}$$

Or, the maximum, or "undimmed", LED current would then be,

$$I_{AVE(UNDIM)} = I_{L2-PK(UNDIM)} - \frac{\Delta i_L}{2}$$

This is important to calculate because this peak current multiplied by the sense resistor  $R3$  will determine when the internal comparator is tripped. The internal comparator turns the control MOSFET off once the peak sensed voltage reaches 750 mV.

$$I_{L-PK(UNDIM)} = \frac{750 \text{ mV}}{R3}$$

**Current Limit:** Under normal circumstances, the trip voltage on the PWM comparator would be less than or equal to 750 mV, depending on the amount of dimming. However, if there is a short circuit or an excessive load on the output, higher than normal switch currents will cause a voltage above 1.27V on the ISNS pin which will trip the I-LIM comparator. The I-LIM comparator will reset the RS latch, turning off Q2. It will also inhibit the Start Pulse Generator and the COFF comparator by holding the COFF pin low. A delay circuit will prevent the start of another cycle for 180  $\mu$ s.

## VALLEY FILL CAPACITORS

Determining voltage rating and capacitance value of the valley-fill capacitors:

The maximum voltage seen by the valley-fill capacitors is:

$$V_{VF-CAP} = \frac{V_{AC(MAX)}\sqrt{2}}{\#stages}$$

This is, of course, if the capacitors chosen have identical capacitance values and split the line voltage equally. Often a 20% difference in capacitance could be observed between like capacitors. Therefore a voltage rating margin of 25% to 50% should be considered.

### Determining the capacitance value of the valley-fill capacitors:

The valley fill capacitors should be sized to supply energy to the buck converter ( $V_{BUCK}$ ) when the input line is less than its peak divided by the number of stages used in the valley fill ( $t_x$ ). The capacitance value should be calculated when the triac is not firing, i.e. when full LED current is being drawn by the LED string. The maximum power is delivered to the LED string at this time, and therefore the most capacitance will be needed.

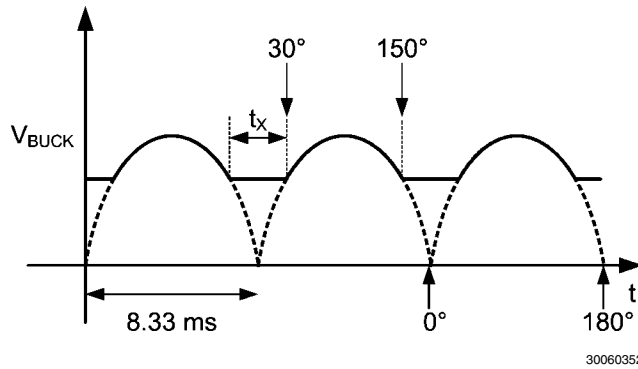


FIGURE 19. Two Stage Valley-Fill  $V_{BUCK}$  Voltage with no TRIAC Dimming

From the above illustration and the equation for current in a capacitor,  $i = C \times dV/dt$ , the amount of capacitance needed at  $V_{BUCK}$  will be calculated as follows:

At 60Hz, and a valley-fill circuit of two stages, the hold up time ( $t_x$ ) required at  $V_{BUCK}$  is calculated as follows. The total angle of an AC half cycle is 180° and the total time of a half AC line cycle is 8.33 ms. When the angle of the AC waveform is at 30° and 150°, the voltage of the AC line is exactly ½ of its peak. With a two stage valley-fill circuit, this is the point where the LED string switches from power being derived from AC line to power being derived from the hold up capacitors (C7 and C9). 60° out of 180° of the cycle or 1/3 of the cycle the power is derived from the hold up capacitors ( $1/3 \times 8.33 \text{ ms} = 2.78 \text{ ms}$ ). This is equal to the hold up time (dt) from the above equation, and dv is the amount of voltage the circuit is allowed to droop. From the next section ("Determining Maximum Number of Series Connected LEDs Allowed") we know the minimum  $V_{BUCK}$  voltage will be about 45V for a 90V<sub>AC</sub> to 135V<sub>AC</sub> line. At 90V<sub>AC</sub> low line operating condition input, ½ of the peak voltage is 64V. Therefore with some margin the voltage at  $V_{BUCK}$  can not droop more than about 15V (dv). (i) is equal to ( $P_{OUT}/V_{BUCK}$ ), where  $P_{OUT}$  is equal to ( $V_{LED} \times I_{LED}$ ). Total capacitance (C7 in parallel with C9) can now be calculated. See "Design Example" section for further calculations of the valley-fill capacitors.

### Determining Maximum Number of Series Connected LEDs Allowed:

The LM3445 is an off-line buck topology LED driver. A buck converter topology requires that the input voltage ( $V_{BUCK}$ ) of the output circuit must be greater than the voltage of the LED stack ( $V_{LED}$ ) for proper regulation. One must determine what the minimum voltage observed by the buck converter will be before the maximum number of LEDs allowed can be determined. Two variables will have to be determined in order to accomplish this.

1. AC line operating voltage. This is usually 90V<sub>AC</sub> to 135V<sub>AC</sub> for North America. Although the LM3445 can

operate at much lower and higher input voltages a range is needed to illustrate the design process.

2. How many stages are implemented in the valley-fill circuit (1, 2 or 3).

In this example the most common valley-fill circuit will be used (two stages).

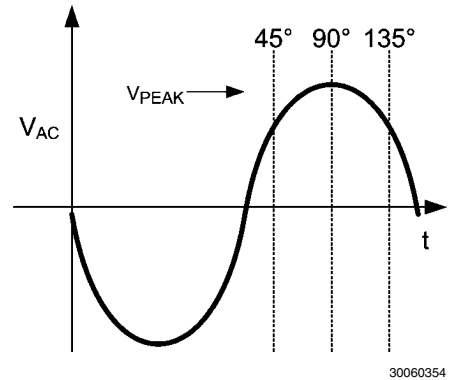


FIGURE 20. AC Line with Firing Angles

Figure 21 show three triac dimmed waveforms. One can easily see that the peak voltage ( $V_{PEAK}$ ) from 0° to 90° will always be:

$$V_{AC-RMS-PK}\sqrt{2}$$

Once the triac is firing at an angle greater than 90° the peak voltage will lower and equal to:

$$V_{AC-RMS-PK}\sqrt{2} \times \text{SIN}(\theta)$$

The voltage at  $V_{BUCK}$  with a valley fill stage of two will look similar to the waveforms of figure 22.

The purpose of the valley fill circuit is to allow the buck converter to pull power directly off of the AC line when the line voltage is greater than its peak voltage divided by two (two stage valley fill circuit). During this time, the capacitors within the valley fill circuit (C7 and C8) are charged up to the peak of the AC line voltage. Once the line drops below its peak divided by two, the two capacitors are placed in parallel and deliver power to the buck converter. One can now see that if the peak of the AC line voltage is lowered due to variations in the line voltage, or if the triac is firing at an angle above 90°, the DC offset ( $V_{DC}$ ) will lower.  $V_{DC}$  is the lowest value that voltage  $V_{BUCK}$  will encounter.

$$V_{BUCK(MIN)} = \frac{V_{AC-RMS(MIN)}\sqrt{2} \times \text{SIN}(\theta)}{\text{\#stages}}$$

Example:

Line voltage = 90V<sub>AC</sub> to 135V<sub>AC</sub>

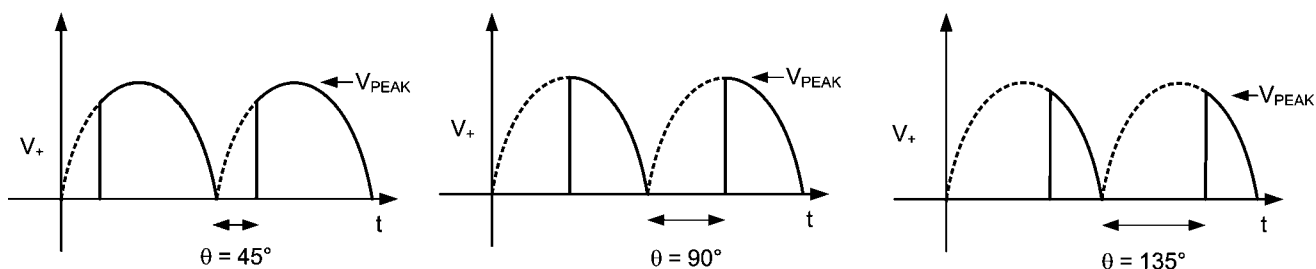
Valley-Fill = two stage

$$V_{BUCK(MIN)} = \frac{90\sqrt{2} \times \text{SIN}(135^\circ)}{2} = 45V$$

Depending on what type and value of capacitors are used, some derating should be used for voltage droop when the

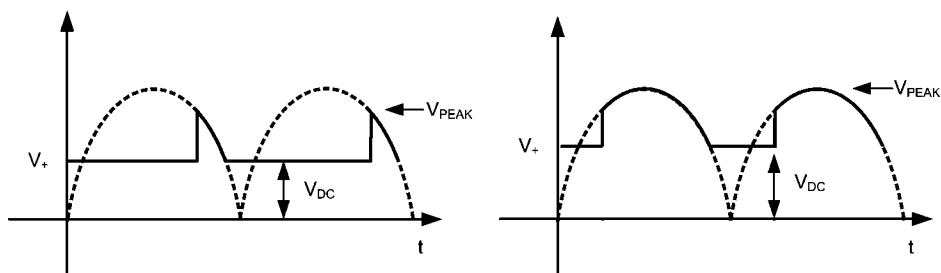
capacitors are delivering power to the buck converter. When the triac is firing at 135° the current through the LED string will be small. Therefore the droop should be small at this point

and a 5% voltage droop should be a sufficient derating. With this derating, the lowest voltage the buck converter will see is about 42.5V in this example.



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FIGURE 21. AC Line with Various Firing Angles



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FIGURE 22.  $V_{BUCK}$  Waveforms with Various Firing Angles

To determine how many LEDs can be driven, take the minimum voltage the buck converter will see (42.5V) and divide it by the worst case forward voltage drop of a single LED.

Example:  $42.5V/3.7V = 11.5$  LEDs (11 LEDs with margin)

#### OUTPUT CAPACITOR

A capacitor placed in parallel with the LED or array of LEDs can be used to reduce the LED current ripple while keeping the same average current through both the inductor and the LED array. With a buck topology the output inductance ( $L_2$ ) can now be lowered, making the magnetics smaller and less expensive. With a well designed converter, you can assume that all of the ripple will be seen by the capacitor, and not the LEDs. One must ensure that the capacitor you choose can handle the RMS current of the inductor. Refer to manufacturer's datasheets to ensure compliance. Usually an X5R or X7R capacitor between 1  $\mu$ F and 10  $\mu$ F of the proper voltage rating will be sufficient.

#### SWITCHING MOSFET

The main switching MOSFET should be chosen with efficiency and robustness in mind. The maximum voltage across the switching MOSFET will equal:

$$V_{DS(MAX)} = V_{AC-RMS(MAX)}\sqrt{2}$$

The average current rating should be greater than:

$$I_{DS-MAX} = I_{LED(AVE)}(D_{MAX})$$

#### RE-CIRCULATING DIODE

The LM3445 Buck converter requires a re-circulating diode D10 (see the Typical Application circuit figure 4) to carry the inductor current during the MOSFET Q2 off-time. The most efficient choice for D10 is a diode with a low forward drop and near-zero reverse recovery time that can withstand a reverse voltage of the maximum voltage seen at  $V_{BUCK}$ . For a common  $110V_{AC} \pm 20\%$  line, the reverse voltage could be as high as 190V.

$$V_D \geq V_{AC-RMS(MAX)}\sqrt{2}$$

The current rating must be at least:

$$I_D = 1 - (D_{MIN}) \times I_{LED(AVE)}$$

Or:

$$I_D = \left(1 - \frac{V_{LED(MIN)}}{V_{BUCK(MAX)}}\right) \times I_{LED(AVE)}$$

## Design Example

The following design example illustrates the process of calculating external component values.

### Known:

1. Input voltage range ( $90V_{AC} - 135V_{AC}$ )
2. Number of LEDs in series = 7
3. Forward voltage drop of a single LED = 3.6V
4. LED stack voltage =  $(7 \times 3.6V) = 25.2V$

### Choose:

1. Nominal switching frequency,  $f_{SW-TARGET} = 250 \text{ kHz}$
2.  $I_{LED(AVE)} = 400 \text{ mA}$
3.  $\Delta i$  (usually 15% - 30% of  $I_{LED(AVE)}$ ) =  $(0.30 \times 400 \text{ mA}) = 120 \text{ mA}$
4. Valley fill stages (1,2, or 3) = 2
5. Assumed minimum efficiency = 80%

### Calculate:

1. Calculate minimum voltage  $V_{BUCK}$  equals:

$$V_{BUCK(MIN)} = \frac{90\sqrt{2} \times \sin(135^\circ)}{2} = 45V$$

2. Calculate maximum voltage  $V_{BUCK}$  equals:

$$V_{BUCK(MAX)} = 135\sqrt{2} = 190V$$

3. Calculate  $t_{OFF}$  at  $V_{BUCK}$  nominal line voltage:

$$t_{OFF} = \frac{\left(1 - \frac{1}{0.8} \times \frac{25.2V}{115\sqrt{2}}\right)}{(250 \text{ kHz})} = 3.23 \mu\text{s}$$

4. Calculate  $t_{ON(MIN)}$  at high line to ensure that  $t_{ON(MIN)} > 200 \text{ ns}$ :

$$t_{ON(MIN)} = \frac{\left(\frac{1}{0.8} \times \frac{25.2V}{135\sqrt{2}}\right)}{\left(1 - \frac{1}{0.8} \times \frac{25.2V}{135\sqrt{2}}\right)} \times 3.23 \mu\text{s} = 638 \text{ ns}$$

5. Calculate C11 and R4:
6. Choose current through R4: (between  $50 \mu\text{A}$  and  $100 \mu\text{A}$ )  $70 \mu\text{A}$

$$R4 = \frac{V_{LED}}{I_{COLL}} = 360 \text{ k}\Omega$$

7. Use a standard value of  $365 \text{ k}\Omega$

8. Calculate C11:

- 9.

$$C11 = \left(\frac{V_{LED}}{R4}\right) \left(\frac{t_{OFF}}{1.276}\right) = 175 \text{ pF}$$

10. Use standard value of  $120 \text{ pF}$

11. Calculate ripple current:  $400 \text{ mA} \times 0.30 = 120 \text{ mA}$

12. Calculate inductor value at  $t_{OFF} = 3 \mu\text{s}$ :

$$L2 = \frac{25.2V \left(1 - \frac{1}{0.8} \times \frac{25.2V}{115\sqrt{2}}\right)}{(350 \text{ kHz} \times 0.1A)} = 580 \mu\text{H}$$

13. Choose C10:  $1.0 \mu\text{F}$   $200V$

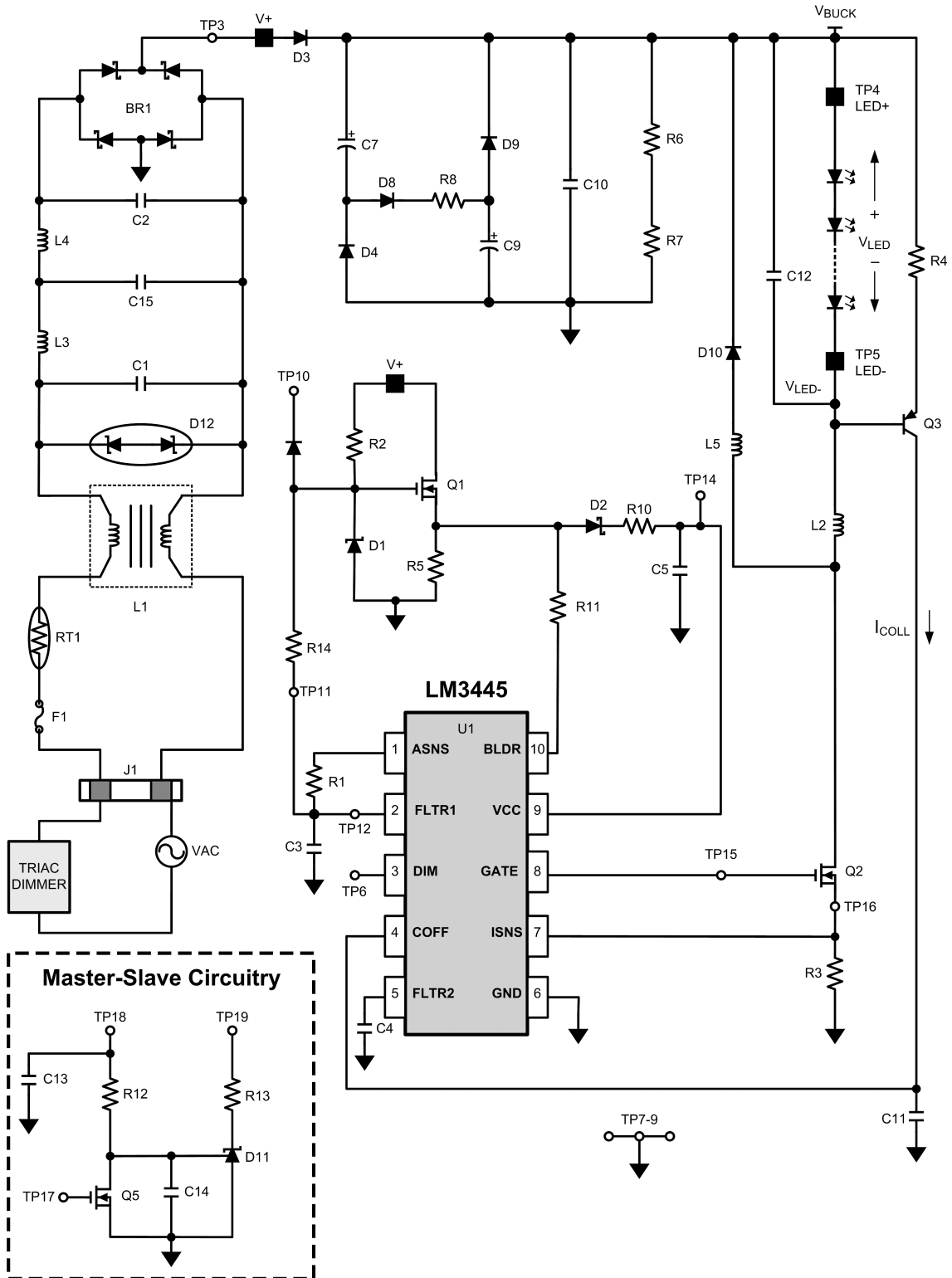
14. Calculate valley-fill capacitor values:  $V_{AC}$  low line =  $90V_{AC}$ ,  $V_{BUCK}$  minimum equals  $60V$  (no triac dimming at maximum LED current). Set droop for  $20V$  maximum at full load and low line.

$$i = C \frac{dv}{dt}$$

i) equals  $P_{OUT}/V_{BUCK}$  ( $270 \text{ mA}$ ),  $dV$  equals  $20V$ ,  $dt$  equals  $2.77 \text{ ms}$ , and then  $C_{TOTAL}$  equals  $37 \mu\text{F}$ . Therefore  $C7 = C9 = 22 \mu\text{F}$

# LM3445 Design Example 1

Input = 90V<sub>AC</sub> to 135V<sub>AC</sub>, V<sub>LED</sub> = 7 x HB LED String Application @ 400 mA



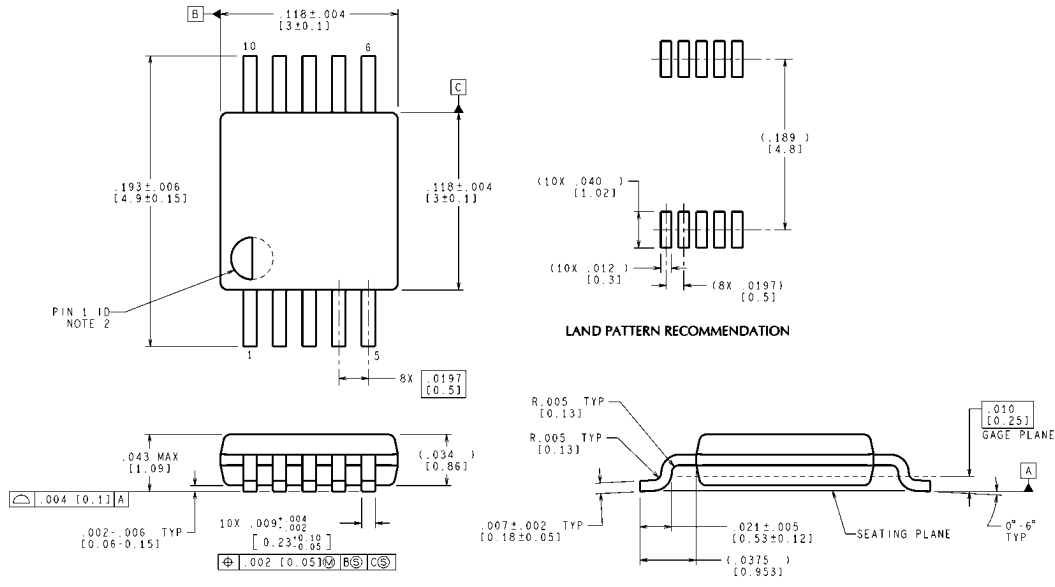
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## Bill of Materials

Qty	Ref Des	Description	Mfr	Mfr PN
1	U1	IC, CTRLR, DRVR-LED, MSOP10	NSC	LM3445MM
1	BR1	Bridge Rectifier, SMT, 400V, 800 mA	DiodesInc	HD04-T
1	L1	Common mode filter DIP4NS, 900 mA, 700 $\mu$ H	Panasonic	ELF-11090E
1	L2	Inductor, SHLD, SMT, 1A, 470 $\mu$ H	Coilcraft	MSS1260-474-KLB
2	L3, L4	Diff mode inductor, 500 mA 1 mH	Coilcraft	MSS1260-105KL-KLB
1	L5	Bead Inductor, 160 $\Omega$ , 6A	Steward	HI1206T161R-10
3	C1, C2, C15	Cap, Film, X2Y2, 12.5MM, 250V <sub>AC</sub> , 20%, 10 nF	Panasonic	ECQ-U2A103ML
1	C3	Cap, X7R, 0603, 16V, 10%, 470 nF	MuRata	GRM188R71C474KA88D
1	C4	Cap, X7R, 0603, 16V, 10%, 100 nF	MuRata	GRM188R71C104KA01D
2	C5, C6	Cap, X5R, 1210, 25V, 10%, 22 $\mu$ F	MuRata	GRM32ER61E226KE15L
2	C7, C9	Cap, AL, 200V, 105C, 20%, 33 $\mu$ F	UCC	EKXG201ELL330MK20S
1	C10	Cap, Film, 250V, 5%, 10 nF	Epcos	B32521C3103J
1	C12	Cap, X7R, 1206, 50V, 10%, 1.0 $\mu$ F	Kemet	C1206F105K5RACTU
1	C11	Cap, C0G, 0603, 100V, 5%, 120 pF	MuRata	GRM1885C2A121JA01D
1	C13	Cap, X7R, 0603, 50V, 10%, 1.0 nF	Kemet	C0603C102K5RACTU
1	C14	Cap, X7R, 0603, 50V, 10%, 22 nF	Kemet	C0603C223K5RACTU
1	D1	Diode, ZNR, SOT23, 15V, 5%	OnSemi	BZX84C15LT1G
2	D2, D13	Diode, SCH, SOD123, 40V, 120 mA	NXP	BAS40H
4	D3, D4, D8, D9	Diode, FR, SOD123, 200V, 1A	Rohm	RF071M2S
1	D10	Diode, FR, SMB, 400V, 1A	OnSemi	MURS140T3G
1	D11	IC, SHNT, ADJ, SOT23, 2.5V, 0.5%	TI	TL431BIDBZR
1	D12	TVS, VBR = 144V	Fairchild	SMBJ130CA
1	R1	Resistor, 0603, 1%, 280 k $\Omega$	Panasonic	ERJ-3EKF2803V
1	R2	Resistor, 1206, 1%, 100 k $\Omega$	Panasonic	ERJ-8ENF1003V
1	R3	Resistor, 1210, 5%, 1.8 $\Omega$	Panasonic	ERJ-14RQJ1R8U
1	R4	Resistor, 0603, 1%, 576 k $\Omega$	Panasonic	ERJ-3EKF5763V
1	R5	Resistor, 1206, 1%, 1.00 k $\Omega$	Panasonic	ERJ-8ENF1001V
2	R6, R7	Resistor, 0805, 1%, 1.00 M $\Omega$	Rohm	MCR10EZHF1004
2	R8, R10	Resistor, 1206, 0.0 $\Omega$	Yageo	RC1206JR-070RL
1	R9	Resistor, 1812, 0.0 $\Omega$		
1	R11	Resistor, 0603, 0.0 $\Omega$	Yageo	RC0603JR-070RL
1	R12	Resistor, 0603, 1%, 33.2 k $\Omega$	Panasonic	ERJ-3EKF3322V
1	R13	Resistor, 0603, 1%, 2.0 k $\Omega$	Panasonic	ERJ-3EKF2001V
1	R14	Resistor, 0805, 1%, 3.3 M $\Omega$	Rohm	MCR10EZHF3304
1	RT1	Thermistor, 120V, 1.1A, 50 $\Omega$ @ 25 $^{\circ}$ C	Thermometrics	CL-140
2	Q1, Q2	XSTR, NFET, DPAK, 300V, 4A	Fairchild	FQD7N30TF
1	Q3	XSTR, PNP, SOT23, 300V, 500 mA	Fairchild	MMBTA92
1	Q5	XSTR, NFET, SOT23, 100V, 170 mA	Fairchild	BSS123
1	J1	Terminal Block 2 pos	Phoenix Contact	1715721
1	F1	Fuse, 125V, 1,25A	bel	SSQ 1.25



**Physical Dimensions** inches (millimeters) unless otherwise noted



CONTROLLING DIMENSION IS INCH  
 VALUES IN [ ] ARE MILLIMETERS  
 DIMENSIONS IN ( ) FOR REFERENCE ONLY

MUB10A (Rev B)

**MSOP-10 Pin Package (MM)**  
**For Ordering, Refer to Ordering Information Table**  
**NS Package Number MUB10A**

## Notes

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Clock and Timing	<a href="http://www.national.com/timing">www.national.com/timing</a>	Reference Designs	<a href="http://www.national.com/refdesigns">www.national.com/refdesigns</a>
Data Converters	<a href="http://www.national.com/adc">www.national.com/adc</a>	Samples	<a href="http://www.national.com/samples">www.national.com/samples</a>
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LVDS	<a href="http://www.national.com/lvds">www.national.com/lvds</a>	Packaging	<a href="http://www.national.com/packaging">www.national.com/packaging</a>
Power Management	<a href="http://www.national.com/power">www.national.com/power</a>	Green Compliance	<a href="http://www.national.com/quality/green">www.national.com/quality/green</a>
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LDOs	<a href="http://www.national.com/ldo">www.national.com/ldo</a>	Quality and Reliability	<a href="http://www.national.com/quality">www.national.com/quality</a>
LED Lighting	<a href="http://www.national.com/led">www.national.com/led</a>	Feedback/Support	<a href="http://www.national.com/feedback">www.national.com/feedback</a>
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PowerWise® Solutions	<a href="http://www.national.com/powerwise">www.national.com/powerwise</a>	Solutions	<a href="http://www.national.com/solutions">www.national.com/solutions</a>
Serial Digital Interface (SDI)	<a href="http://www.national.com/sdi">www.national.com/sdi</a>	Mil/Aero	<a href="http://www.national.com/milaero">www.national.com/milaero</a>
Temperature Sensors	<a href="http://www.national.com/tempensors">www.national.com/tempensors</a>	SolarMagic™	<a href="http://www.national.com/solarmagic">www.national.com/solarmagic</a>
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