High-Brightness LED Lighting Solutions

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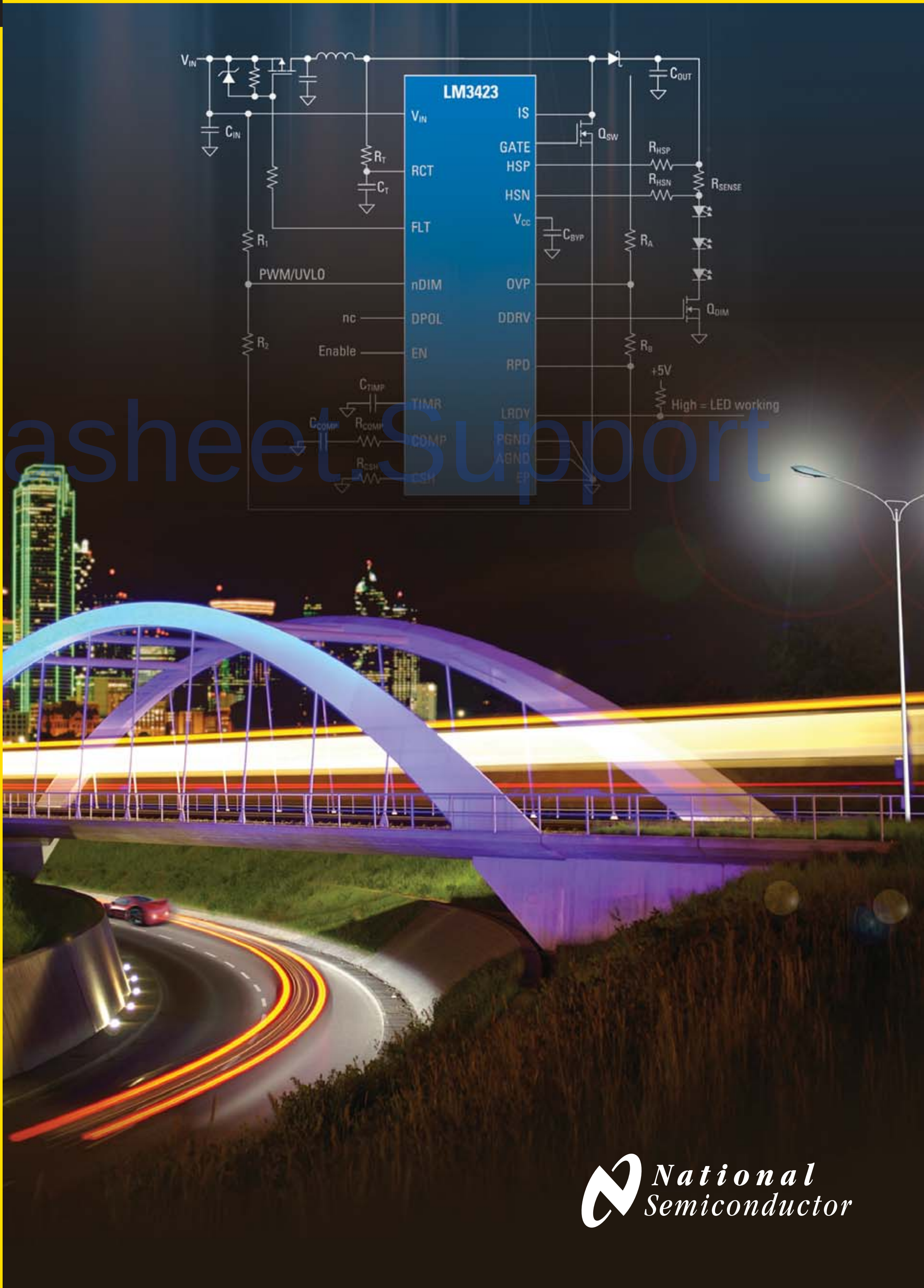


National Semiconductor

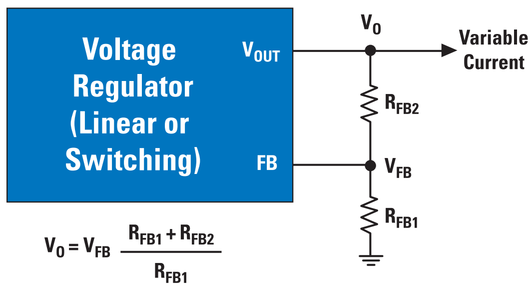
Overview

Regardless of type, color, size, or power, all LEDs work best when driven with a constant current. LED manufacturers specify the characteristics (such as lumens, beam pattern, color) of their devices at a specified forward current (I_F) not at a specific forward voltage (V_F). Most power supply ICs are designed to provide constant voltage outputs over a range of currents (see below), hence it can be difficult to ascertain which parts will work for a given application from the device datasheet alone. With an array of LEDs, the main challenge is to ensure every LED in the array is driven with the same current. Placing all the LEDs in a series string ensures that exactly the same current flows through each device.

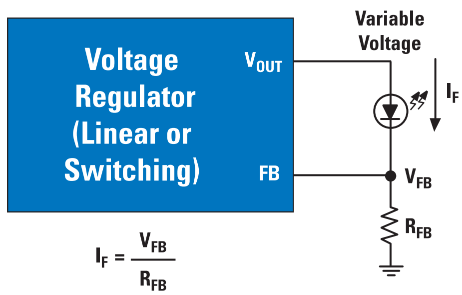
High-Brightness LEDs: Input Voltage and Forward Voltage

Sources of input voltage for LED arrays come from batteries or power supplies that have a certain tolerance. An automotive battery, for example, may supply 8V to 16V depending on the load and the age of the battery. The 'silver box' power supply inside a desktop CPU may supply 12V ±10%. High-brightness (HB) LEDs also give a range of forward voltage. A typical HB LED might be characterized at a forward current of 350 mA. The forward voltage of the LED when I_F = 350 mA is specified with a range that includes a typical value as well as over-temperature maximum and minimum values. To ensure that a true constant current is delivered to each LED in an array, the power topology must be able to deliver an output voltage equal to the sum of the maximum forward voltages of every device placed in the string. Manufacturers bin their devices for color, brightness, and forward voltage. Binning for all three characteristics is expensive, and forward voltage is often the specification that is allowed to vary the most. Adding this to the shift in forward voltage as the LED die temperature changes gives rise to the need for constant current regulators that have a wide range of output voltage.

Constant Voltage Regulator



Constant Current Regulator



When Input Voltage Exceeds LED Voltage

If input voltage always exceeds the sum of the maximum forward voltages of every LED in a string, then two options are available: linear regulators and buck regulators.

A linear regulator introduces efficiency and thermal drawbacks, but is the simplest design option. In order to provide constant current, the linear regulator must be an adjustable type that uses a pair of feedback resistors. Replacing the top feedback resistor with the LED string and placing a current-sensing resistor in the bottom position ‘tricks’ the former constant voltage source into adjusting the output voltage until enough current flows through the current-sensing resistor to equal the feedback voltage of the IC. Linear regulators have the advantages of simplicity and low part count, and generate no EMI. They can deliver constant current as long as the V_F in the LED string does not exceed their dropout limited output voltage. The disadvantage lies in efficiency and thermal dissipation. Loss in a linear regulator LED driver is approximately equal to $(V_{IN} – n \times V_F) \times I_F$, where ‘n’ is the number of LEDs in the string. At currents of 350 mA and above, the linear solution may require a heatsink, adding cost and size to the design.

The more efficient option when input voltage always exceeds the LED voltage is a step-down or buck regulator. As with linear regulators, this must be an adjustable type, and the same method can be used to turn almost any buck regulator into a constant current source for LEDs. Buck regulators enjoy high efficiency and eliminate the need for a heatsink, at the cost of a more complex circuit and the addition of switching noise. Many recent buck regulators switch at 1 MHz and above, making their external components so small that at currents under 1A they may actually use less space than a linear regulator.

When Input Voltage is Less than LED Voltage

When the minimum forward voltage of all the LEDs in a string will always exceed the maximum input voltage, a step-up, or boost regulator is needed.

The inductive-boost converter is the simplest regulator that can deliver currents above 350 mA with a varying output voltage. As with linear and buck regulators, a boost converter with a feedback-divider network can be modified to become a constant current source. One important distinction between the buck regulator and boost regulator must be made when the power switch is internal to the control IC. Such monolithic systems have a fixed current limit. In buck regulators, the internal switch passes the same DC current as the LED. A boost converter differs in that the internal switch sees a higher current that varies with input voltage; the greater the difference between V_{IN} and V_{OUT}, the higher the internal switch current. Care must be taken to evaluate a monolithic boost regulator-based LED drive to make sure that it will not hit the fixed current limit over the range of input voltage.

When Input Voltage Range Overlaps LED Voltage Range

As HB LEDs are adopted into more and more applications, situations will arise when the input voltage varies above and below the forward voltage of the LED string. For these cases, a current regulator is needed that can both buck and boost as required by the input and output conditions. Possible topologies include the buck-boost, SEPIC, Cuk, flyback, and V_{IN} referenced boost (also called the floating buck-boost). In all of these topologies, the power-switch current exceeds the LED current and varies with input voltage. The same attention to peak switch current must be made over the full range of input voltage, especially if a regulator with an internal power switch and fixed current limit is implemented.

For more information about National’s LED products, samples, design simulation tools, and more visit: national.com/LED.

LED Drivers and Controllers

Switched-Capacitor Boost High-Power LED Drivers

Product ID	Input Range (V)	Output Voltage (V)	Current or Voltage Sourced	Total LED Current (mA)	Switching Frequency (MHz)	Number of LEDs	Dimming Type	Packaging
LM2753	3 to 5.5	5	Voltage	400	0.725	1	Analog	LLP-10
LM2754	2.8 to 5.5	5	Current	800	1	1 to 4	Analog	LLP-24

Inductive Boost High-Brightness LED Drivers

Product ID	Input Range (V)	Max Output Voltage (V)	Typical Switch Current (mA)	Switching Frequency (MHz)	Number of LEDs	Dimming Type	Key Features	Packaging
LM3224	2.7 to 7	20	2450	0.6/1.25	1	PWM	White-LED flash/torch application	MSOP-8
LM3553	2.7 to 5.5	18.9	2200	1.2	1 to 2	Analog	1.2A flash LED driver with I^2C Compatible Interface	LLP-12
LM2698	2.2 to 12	17.5	1900	0.6/1.25	1 to 4	Analog	1.9A switch, input undervoltage	MSOP-8
LM2700	2.2 to 12	17.5	3600	0.6/1.25	1 to 4	Analog	3.6A switch, input undervoltage	TSSOP-14, LLP-14
LM2735x/y	2.7 to 5.5	24	2450	0.55/1.6	1 to 5	Analog	2.45A switch, internally compensated	SOT23-5, LLP-6, eMSOP-8
LM5000	3.1 to 40	75	2000	0.3/0.7/0.6/1.2	1 to 20	Analog	2A switch, no compensation required	TSSOP-16, LLP-16
LM5001	3.1 to 75	75	1000	Up to 1.5	1 to 20	Analog	1A switch, no compensation required	SO-8, LLP-8
LM5002	3.1 to 75	75	500	Up to 1.5	1 to 20	Analog	500 mA switch, internally compensated	SO-8, LLP-8
LM2733	2.7 to 14	40	1000	0.6/1.6	1 to 8	Analog	1A switch, internally compensated	SOT23-5
LM27313	2.7 to 14	30	800	1.6	1 to 6	Analog	800 mA switch, internally compensated	SOT23-5
NEW! **LM3410***	2.7 to 5.5	24	2100	0.525/1.6	1 to 5	PWM	Ultra-low stand by current of 80 nA, internally compensated	SOT23-5, LLP-6, eMSOP-8

* Preferred device: This part, featuring high efficiency and ease-of-use, is specifically designed for driving high-brightness LEDs.

PowerWise product

Inductive Buck High-Brightness LED Drivers

Product ID	Input Range (V)	Output Voltage (V)	Total LED Current (mA)	Switching Frequency (MHz)	Number of LEDs	Dimming Type	Key Features	Packaging
LM3402/HV*	6 to 42/6 to 75	37/67	525	Adjustable up to 1 MHz	1 to 9/15	PWM	200 mV feedback voltage, fast PWM dimming	MSOP-8
LM3404/HV*	6 to 42/6 to 75	37/67	1000	Adjustable up to 1 MHz	1 to 9/15	PWM	200 mV feedback voltage, fast PWM dimming	SOIC-8
NEW! **LM3405A***	3 to 22	20	1000	1.6 MHz	1 to 3	PWM	200 mV feedback voltage, fast PWM dimming, thin package	SOT23-6, eMSOP-8
NEW! **LM3406/HV**	6 to 42/75	37/67	1500	Adjustable up to 1 MHz	1 to 15	PWM/ two-wire	20 mV feedback voltage, fast PWM or two-wire dimming	eTSSOP-14
LM5010/A	8/6 to 75	67	1000	Adjustable up to 1 MHz	1 to 15	PWM	NonSynch, internal high-side N FET	eTSSOP-14, LLP-10
LM5007	9 to 75	67	700	Adjustable up to 800 kHz	1 to 15	PWM	NonSynch, internal high-side N FET	MSOP-8
NEW! **LM3407***	4.5 to 30	27	350	Adjustable up to 1 MHz	1 to 7	PWM	Constant frequency PWM with true average current detection	eMSOP-8

High-Brightness LED Controllers

Product ID	Topology	Input Range (V)	Output Voltage (V)	Max LED Current (mA)	Switching Frequency (MHz)	Number of LEDs	Dimming Type	Key Features	Packaging
NEW! **LM3401***	Buck/ Hysteretic Controller	4.5 to 35	Up to 35	3A	Adjustable to 2 MHz	1 to 9	PWM	Dual-side hysteresis, very low reference voltage and short propagation delay	MSOP-8
NEW! **LM3433***	Buck	9 to 14	Up to 6	14+	Adjustable up to 1 MHz	—	PWM	Negative output voltage capability allows LED anode to be tied directly to chassis for max. heat sink efficacy	LLP-24
LM5020	Buck/Boost/ Flyback	13 to 100	Adjustable	1A+	Adjustable up to 1 MHz	1 to 20	PWM	Flexible LED drive current with external FET, 500 mV feedback voltage	MSOP-10, LLP-10
LM3478	Buck/Boost/ Flyback	2.97 to 40	Adjustable	1A+	Adjustable up to 1 MHz	1 to 9	PWM	Flexible LED drive current with external FET, 200 mV feedback voltage	MSOP-8
LM5022	Buck/Boost/ Flyback	6 to 60	Adjustable	1A	Adjustable up to 2 MHz	1 to 9	PWM	Flexible LED drive current with external FET, 500 mV feedback voltage	MSOP-10
NEW! **LM3421**	Buck/Boost Floating Buck-Boost	4.5 to 75	Adjustable	3A+	Adjustable up to 2 MHz	1 to 20	PWM	20 mV to 1.235V adjustable differential current sense voltage, 50 kHz max PWM dimming	TSSOP-16 EP
NEW! **LM3423**	Buck/Boost Floating Buck-Boost	4.5 to 75	Adjustable	3A+	Adjustable up to 2 MHz	1 to 20	PWM	20 mV to 1.235V adjustable differential current sense voltage, 50 kHz max PWM dimming; fault timer; LED ready flag; highside dimming	TSSOP-20 EP
NEW! **LM3431***	Boost	5 to 36	Up to 40	150 mA/ String	Adjustable up to 1 MHZ	3 channels x 10	Analog, PWM	LED protection: short, open and thermal	eTSSOP-28

* Preferred device: This part, featuring high efficiency and ease-of-use, is specifically designed for driving high-brightness LEDs.

PowerWise product

Switched-Capacitor Solutions

For LED-drive applications, the gain of a switched capacitor converter must be large enough to supply enough boost at minimum V_{IN}, maximum LED voltage, and maximum LED current. This must hold over temperature and process variation. More advanced switched-capacitor techniques can improve overall efficiency, but good inductive solutions will almost always have an efficiency advantage over switched-capacitor solutions.

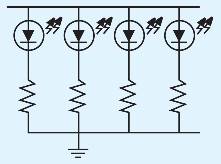
- Switched-capacitor boost LED driver
  – Lower LED voltage = no change in power consumed
  – Lower LED voltage = increase in efficiency value

Parallel Topologies

LEDs in parallel: When LEDs are connected off one wire, next to each other in a row; positive (+) to separate grounds (GND).

Advantage: Not restricted to one power rail; good for keypad applications.

LEDs in Parallel

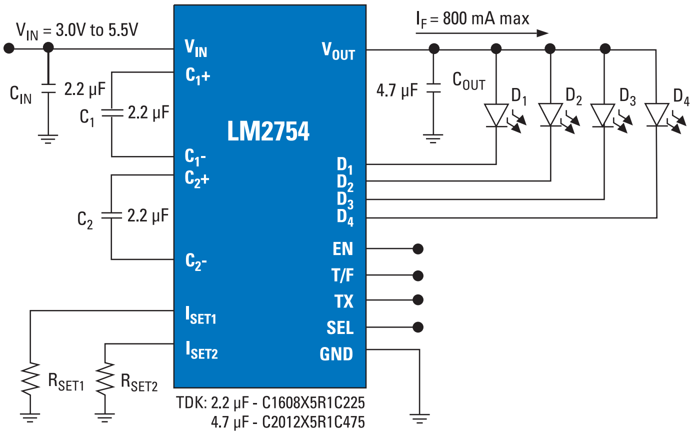


LM2754 – 800 mA Switched Capacitor Flash LED Driver

Theory of Operation

The LM2754 is an integrated low-noise, high-current switched capacitor DC-DC converter with four regulated current sinks. The device is optimized for driving 1 to 4 high-power white LEDs in parallel with a maximum current of 800 mA. Maximum efficiency is achieved over the input voltage range by actively selecting the proper gain based on the LED forward voltage and current requirements. Two external low-power resistors set the desired current for Torch and Flash modes.

LM2754 Typical Application



Inductive-Boost Solutions

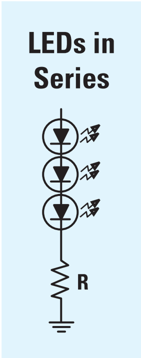
Inductive LED drivers are the best solution for currents greater than a few hundred milliamps. The major advantage to inductive-boost drivers is their ability to drive significantly higher current, which is especially good for applications that need many LEDs or are using an LED flash. Another advantage is that these drivers can continuously adjust their gain (PWM or PFM) to change LED brightness.

- Inductive-boost LED driver
  - Lower LED voltage = less power consumed
  - Lower LED voltage = no change in efficiency value

Series Topologies

LEDs in series: When all LEDs are connected off one wire in a column, one after another; positive (+) to negative (-).

Advantages: Single output pin, guaranteed current matching.

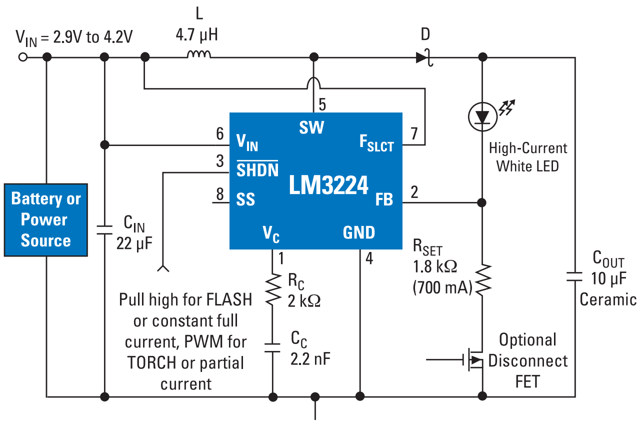


LM3224 – Inductive Step-Up Converter with PWM Control for White-LED Flash/Torch Applications

Theory of Operation

The LM3224 is a step-up DC-DC converter with a 0.15W (typ), 2.45A (typ) internal switch and pin-selectable operating frequency. The LM3224 has the ability to convert 3.3V to multiple outputs of 8V, -8V, and 23V. With a high-current switch, it is also ideal for driving high-current white LEDs for flash applications. The LM3224 can be operated at switching frequencies of 615 kHz and 1.25 MHz, allowing for easy filtering. An external compensation pin gives the user flexibility in setting frequency compensation, which makes the use of small, low-ESR ceramic capacitors at the output possible. An external softstart pin allows the user to limit the voltage overshoot at the load terminals during startup.

LM3224 Typical Application Circuit

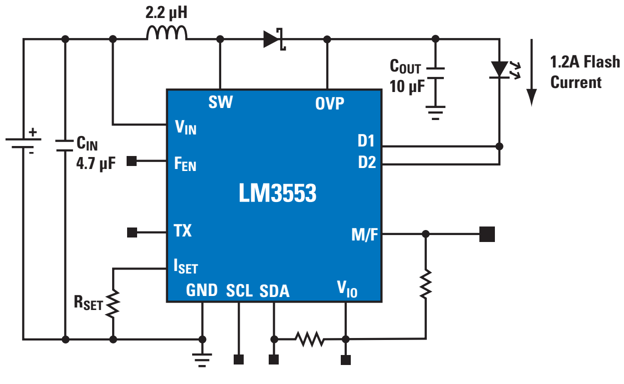


LM3553 – 1.2A PowerWise® Dual Flash LED Driver System with I²C-Compatible Interface

Theory of Operation

The LM3553 is a fixed frequency, current mode step-up DC/DC converter with two regulated current sinks. The device is capable of driving loads up to 1.2A from a single-cell Li-Ion battery. One or more high-current flash LEDs can be driven in series either in a high-power Flash mode or a lower power Torch mode controlled by either an internal register or the FEN pin.

LM3553 Typical Application Circuit



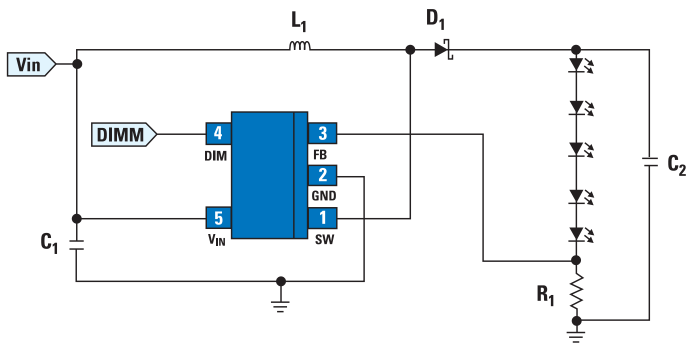
Inductive-Boost LED Drivers

LM3410 – Constant-Current Boost and SEPIC LED Driver with Internal Compensation

Theory of Operation

The LM3410 LED driver is a monolithic, high frequency, PWM step-up DC/DC converter in SOT23-5, LLP-6, and eMSOP-8 packages. With a minimum of external components the LM3410 is easy to use. It can drive 2.5A typical peak currents with an internal 160m NMOS switch. Switching frequency is internally set to either 525 kHz or 1.60 MHz. Even though the operating frequency is high, efficiencies up to 85% are easy to achieve. External shutdown is included, featuring an ultra-low stand-by current of 80 nA. The LM3410 utilizes current-mode control and internal compensation to provide high-performance over a wide range of operating conditions. Additional features include dimming, pulse-by-pulse current limit, and thermal shutdown.

LM3410 Typical Application

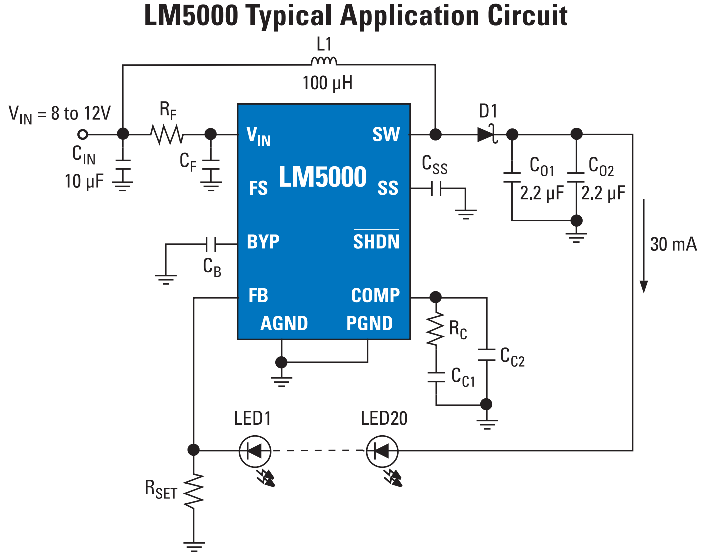


LM5000 – High-Voltage Boost Regulator

Theory of Operation

This circuit boosts the input voltage in order to keep 20 LEDs in a single-series string, ensuring that the same current flows through each device. The high voltage capability of the LM5000 makes it simple to power long strings with no external power switches required.

LM5000 Typical Application Circuit

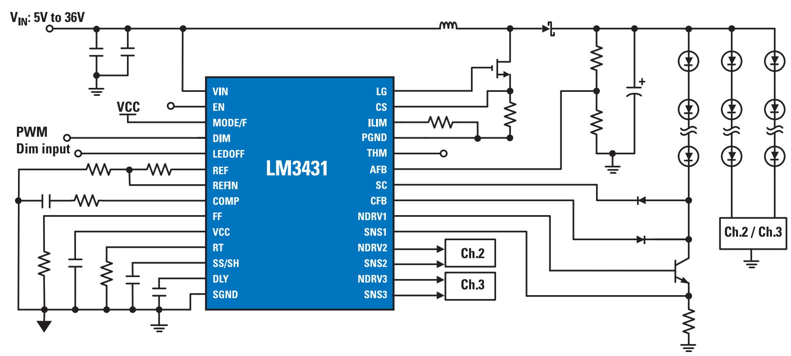


LM3431 – 3-Channel Constant-Current LED Driver with Integrated Boost Controller

Theory of Operation

The LM3431 is a 3-channel linear current controller combined with a boost switching controller ideal for driving LED backlight panels in space critical applications. The LM3431 drives 3 external NPN transistors or MOSFETs to deliver high accuracy constant current to 3 LED strings. Output current is adjustable to drive strings in excess of 200 mA. The boost controller drives an to external NFET switch for step-up regulation from input voltages between 5V to 36V. The LM3431 features LED cathode feedback to minimize regulator headroom and optimize efficiency. A DIM input pin controls LED brightness from analog or digital control signals. Dimming frequencies up to 25 kHz are possible with a contrast ratio of 100:1. Contrast ratios greater than 1000:1 are possible at lower dimming frequencies. The LM3431 eliminates audible noise problems by maintaining constant output voltage regulation during LED dimming. Additional features include LED short and open protection, fault delay/error flag, cycle-by-cycle current limit, and thermal shutdown for both the IC and LED array.

LM3431 Typical Application Circuit

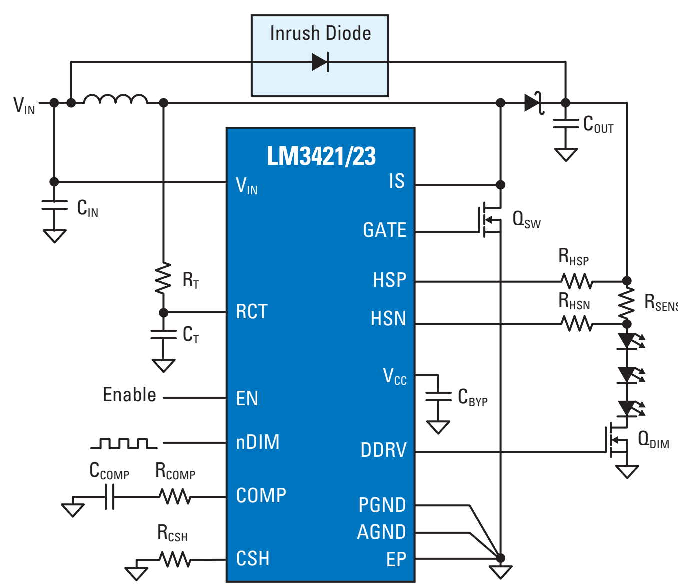


LM3421/23 – PowerWise® N-Channel Controllers for Constant Current LED Drivers

Theory of Operation

The LM3421/23 devices are versatile high-voltage LED driver controllers and can be configured in a Buck, Boost, Buck-Boost (Flyback), or SEPIC topology, these controllers are ideal for illuminating LEDs in a very diverse, large family of applications. Adjustable high-side current sense threshold allows for high-efficiency design. Output LED current regulation is based on peak current-mode control with predictive Off-Time. It eases the design of loop compensation while providing inherent input voltage feed-forward compensation. Adjustable switching frequency is up to 2.0 MHz. Additional features include: "zero" current shutdown, precision reference, fast PWM dimming, cycle-by-cycle current limit, and thermal shutdown etc.

LM3421/23 Typical Application Circuit

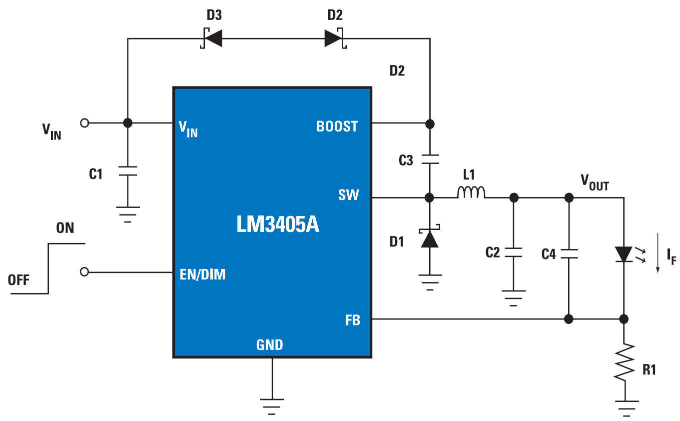


LM3405A – 1A Constant Buck LED Driver with Internal Compensation

Theory of Operation

The LM3405A is a 1A constant-current buck LED driver designed to provide a simple, high-efficiency solution for driving high-power LEDs. With a 0.205V reference voltage feedback control to minimize power dissipation, an external resistor sets the current as needed for driving various types of LEDs. Switching frequency is internally set to 1.6MHz. The LM3405A utilizes current-mode control and internal compensation offering ease of use and predictable, high-performance regulation over a wide range of operating conditions. With a maximum input voltage of 22V, it can drive up to five High-Brightness LEDs in series at 1A forward current, with the single LED forward voltage of approximately 3.7V. Additional features include user accessible EN/DIM pin for enabling and PWM dimming of LEDs, thermal shutdown, cycle-by-cycle current limit and over-current protection.

LM3405A Typical Application

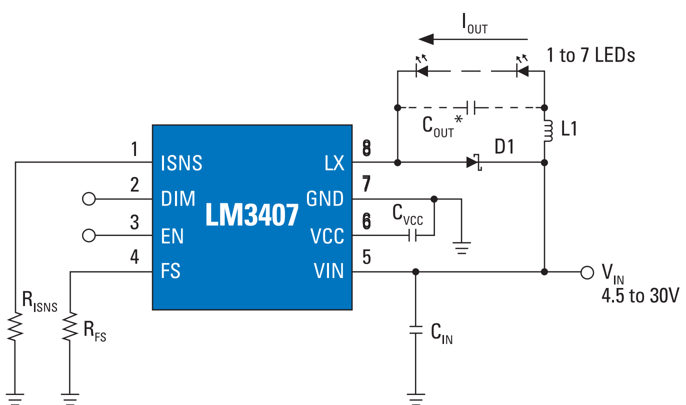


LM3407 – 350 mA, Constant-Current Output Floating Buck Switching Converter for High-Power LEDs

Theory of Operation

The LM3407 is a constant-current output floating buck-switching converter designed to provide constant current to high-power LEDs. The device is ideal for automotive, industrial and general lighting applications. The LM3407 has an integrated power N-MOSFET. An external 1% resistor allows the converter output voltage to adjust as needed to deliver constant current accurately to a serially connected LED string. The switching frequency is adjustable from 300 kHz to 1 MHz. The LM3407 features a dimming input to enable LED brightness control by Pulse Width Modulation (PWM).

LM3407 Typical Application

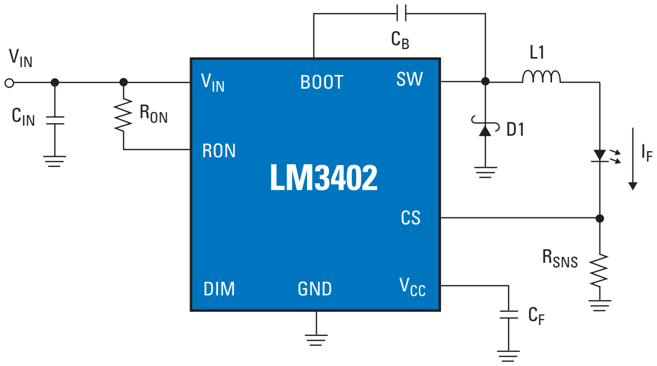


LM3402 – 0.5A LED Driver with 200 mV Feedback Voltage and V_{IN} up to 75V

Theory of Operation

The LM3402/02HV is a compact, efficient constant-current step-down (Buck) monolithic switching regulator designed to drive high-power LEDs. Ideal for automotive, industrial, and general lighting applications, it contains a high-side N-MOSFET switch capable of driving up to 500 mA and a low 200 mV feedback voltage. The wide input voltage range of 6V to 42V for the LM3402 and 6V to 75V for the LM3402HV, makes this an ideal LED driver for a wide range of applications.

LM3402 Typical Application

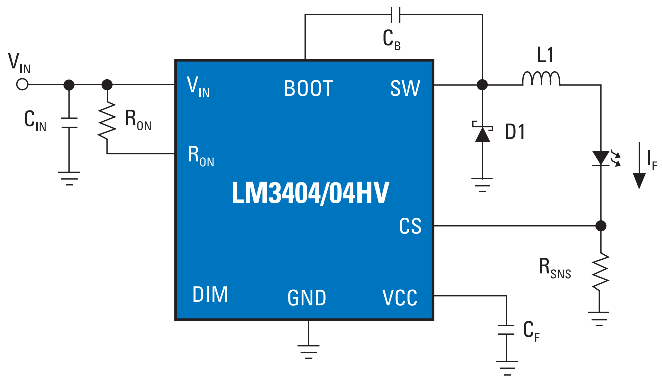


LM3404 – 1.0A Constant-Current Buck Regulator for Driving High-Power LEDs

Theory of Operation

The LM3404/04HV are monolithic switching regulators designed to deliver constant currents to high power LEDs. Ideal for automotive, industrial, and general lighting applications, they contain a high-side N-MOSFET switch with a current limit of 1.2A (typical) for step-down (Buck) regulators. Hysteretic control with controlled on-time, coupled with an external resistor allow the converter output voltage to adjust as needed. Output current dimming via PWM, broken/open LED protection, low-power shutdown and thermal shutdown complete the feature set.

LM3404/04HV Typical Application Circuit

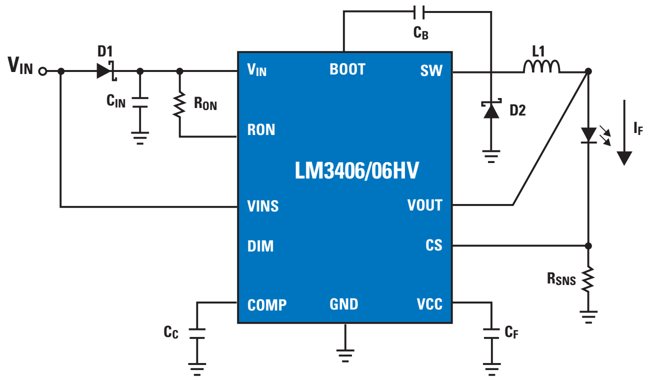


LM3406/06HV – PowerWise® 1.5A Constant-Current Buck Regulator for Driving High-Power LEDs

Theory of Operation

The LM3406/06HV is buck regulator with a wide-input voltage range, low-voltage reference, and a two-wire dimming functions. These features combine to make them ideal for use as a constant-current source for LEDs with forward currents as high as 1.5A. The controlled on-time (COT) architecture uses a comparator and a one-shot on-timer that varies inversely with input and output voltage instead of a fixed clock. The LM3406/06HV also employs an integrator circuit that averages the output current. When the converter runs in continuous conduction mode (CCM) the controlled on-time maintains a constant switching frequency over changes in both input and output voltage. These features combine to give the LM3406/06HV an accurate output current, fast transient response, and constant switching frequency over a wide range of conditions.

LM3406/06HV Typical Application Circuit



Inductive-Buck LED Controllers

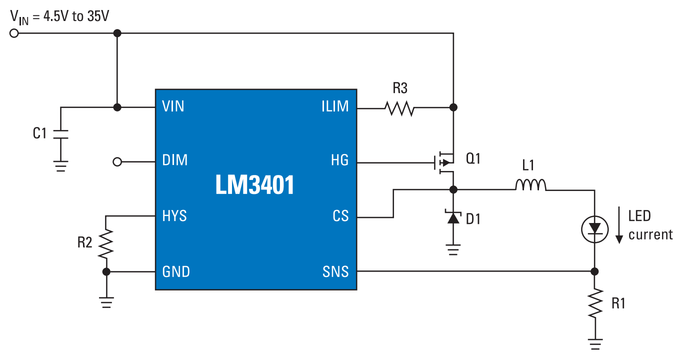
LM3401 – Hysteresis PFET Controller for High-Power LED Driver

Theory of Operation

The LM3401 drives an external P-MOSFET switch for buck regulators. The LM3401 delivers constant current within ±6% accuracy to a wide variety and number of series connected LEDs. Output current is adjusted with an external current sensing resistor to drive high-power LEDs in excess of 1A.

For improved accuracy and efficiency, the LM3401 features dual-side hysteresis, very low reference voltage, and short propagation delay. A cycle-by-cycle current limit provides protection against over current and short circuit failures. Additional features include adjustable hysteresis and a CMOS compatible input pin for PWM dimming.

LM3401 Typical Application

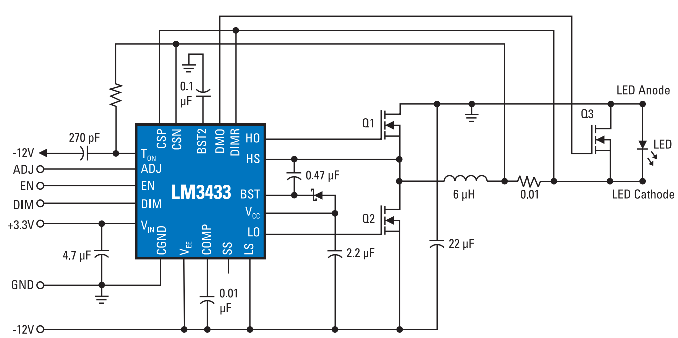


LM3433 – PowerWise® Common Anode Capable High-Brightness LED Driver with High-Frequency Dimming

Theory of Operation

The LM3433 is an adaptive constant on-time DC/DC buck constant current controller (a true current source). The LM3433 provides a constant current for illuminating high-power LEDs. The output configuration allows the anodes of multiple LEDs to be tied directly to the ground referenced chassis for maximum heat sink efficacy. The high-frequency capable architecture allows the use of small external passive components and no output capacitor while maintaining low LED ripple current. The PWM functions by shorting out the LED with a parallel switch allowing high PWM dimming frequencies. Additional features include thermal shutdown, VCC under-voltage lockout, and logic level shutdown mode.

LM3433 Typical Application



High-Brightness LED Reference Designs

Application	Part Used	Description	Page
Portable Torch Lamp	LM2623	Boost converter driving high brightness 1W LED from single or two cell battery pack	14
MR16	LM3405A	12V AC input for MR 16 LED bulbs	15
Automotive Lighting	LM5007	Buck converter for automotive applications, driving 1 to 2 High-Brightness 1W LEDs	16
	LM5010	Buck converter for automotive tail light application, 1 High-Brightness LED, 300 or 900 mA	17
24V BUS Street Lamp	LM3402	6 InGaN white LEDs, 330 mA	18
48V BUS Street Lamp	LM3402HV	12 InGaP LEDs, 360 mA	19
Scanner/MFP Light Source	LM3402	Driving 1-2 InGaN High-Brightness white LEDs , 335 mA, from 12 VDC adaptor	20
		Driving an multiple strings array of 6 series-connected InGaN white LEDs, 330 mA , from 24 VDC adaptor	21
Wide Input Applications	LM3402	1 InGaN LED, 350 mA	22
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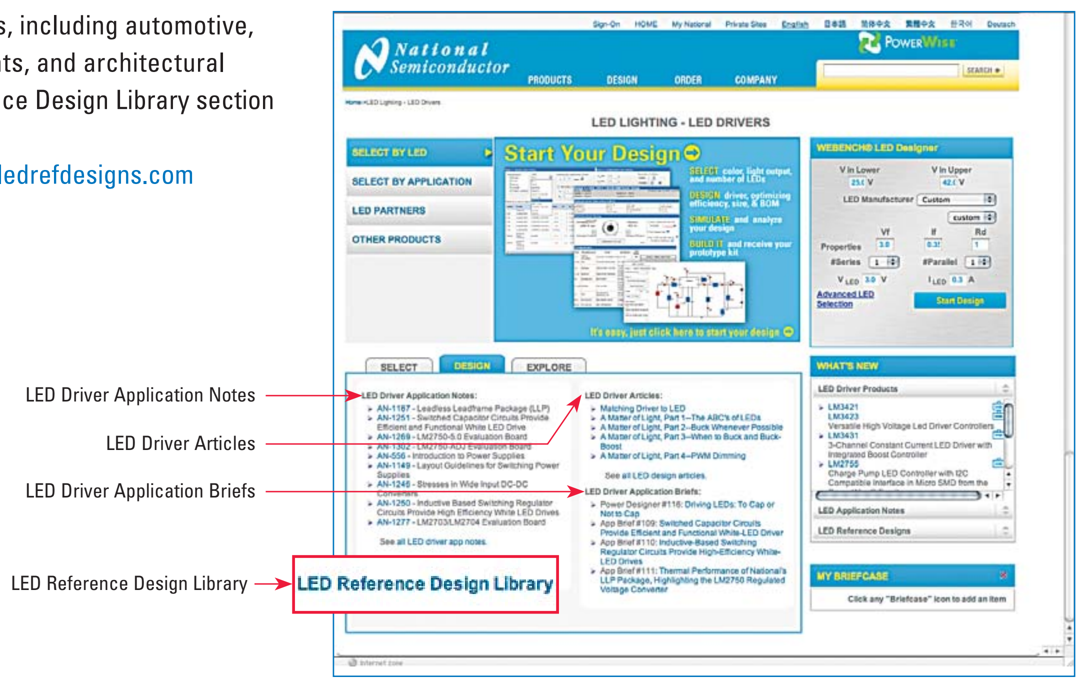
LED Reference Design Library

For more lighting applications, including automotive, general illumination, flashlights, and architectural lighting, visit the LED Reference Design Library section at national.com/LED or visit www.national.com/webench/ledrefdesigns.com



LM2623 – PowerWise® Boost Regulator Driving High-Brightness 1W LED from Single or Two-Cell Battery Pack

Description:

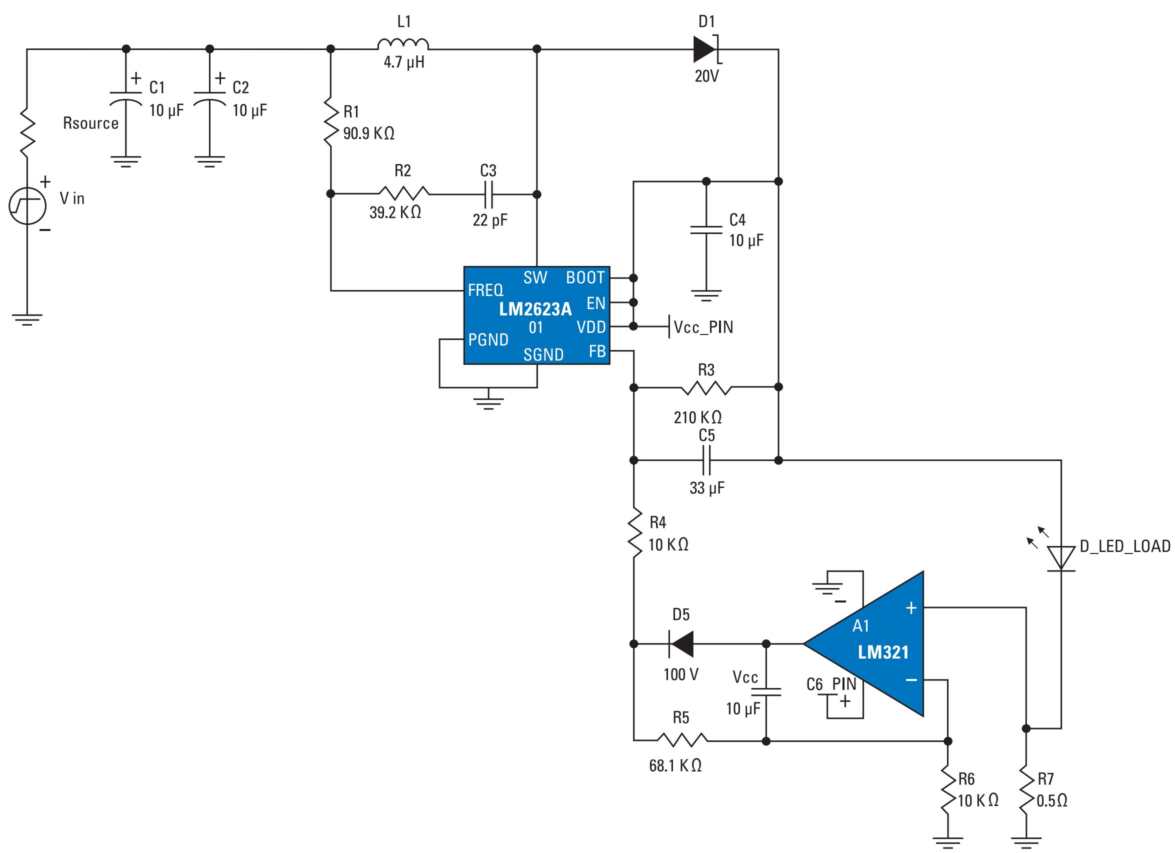
- This design is a basic boost that is capable of providing constant current of 350 mA and an open circuit maximum voltage of 5V at high efficiency.
- It is designed to power 1W LED from a single cell or two cells.

Specification:

Inputs	Output #1
V_{IN} Min = 1.5V	V_{OUT1} = 3.5V (typ)
V_{IN} Max = 3.3V	I_{OUT1} = 0.350A

Theory of Operation

- It uses the LM2623MM, a mini SO-8 package boost switcher with an internal 1.2A switch, to boost the input voltage from 1.5V to 3.3V to the required LED voltage of 3.5V (typ).
- With an LED present, as the output voltage ramps to approximately 3.5V, the LED will turn on causing current to flow through R7.
- The voltage across R7 is amplified by a factor of 7X by the SOT-5 LM321MF and the gain resistors R5 and R6. This produces a voltage of 1.24V at the junction of R4 and R5 when 350 mA flows through the LED. The 1.24V regulates the LED current at a constant value by the internal LM2623 feedback control.
- The LM2623A should be used for single cell operation since it guarantees a peak switch current greater than 2A.



LM3405A – PowerWise® 1.6 MHz, 1A Constant-Current Buck LED Driver

Description:

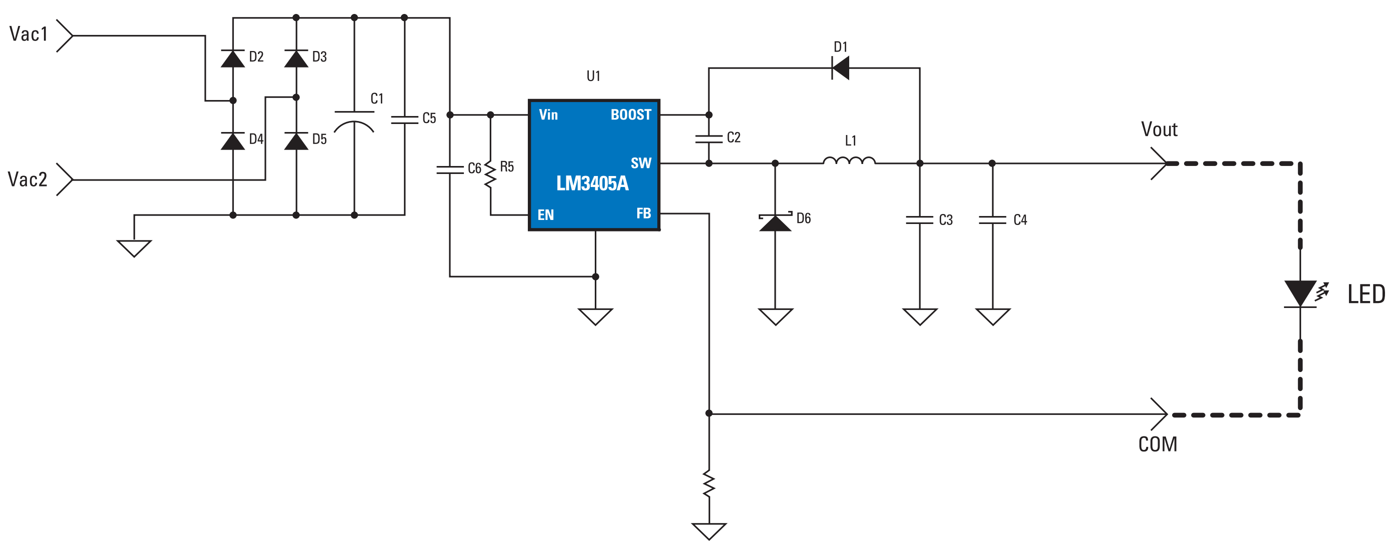
This design is an example of an MR16 form factor LED bulb to replace a halogen light bulb. It is capable of providing 600 mA constant current to drive High-Brightness LEDs from a 12V AC source.

Specification:

Inputs	Output #1
V_{IN} Min = 10.8 VAC	V_{OUT1} = 3.8V
V_{IN} Max = 13.2 VAC	I_{OUT1} = 0.6A

Theory of Operation

- It uses LM3405A LED driver, a current-mode control buck switching regulator in tiny SOT23 package to drive high power LEDs (Typical Vf = 3.8V).
- With a 0.205V reference voltage feedback control to minimize power dissipation, an external resistor sets the current as needed for driving various types of LEDs.
- As the input voltage of MR16 is 12 VAC, a bridge rectifier is required to rectify the AC input to DC level in order to provide supply to LM3405A LED driver. With wide input operating voltage range of the LM3405A (from 3 VDC to 22 VDC), a very small input capacitor can maintain continuous operation.
- Switching frequency is internally set to 1.6 MHz, allowing the use of extremely small surface mount inductors and chip capacitors.
- All these factors help to squeeze the overall dimensions of the PCB to fit the stringent space constraints of the MR16 form factor and this makes LM3405A the best LED driver for this application.



LM5007 – Buck Switching Regulator Driving 1 to 2 High-Brightness 1W LEDs

Description:

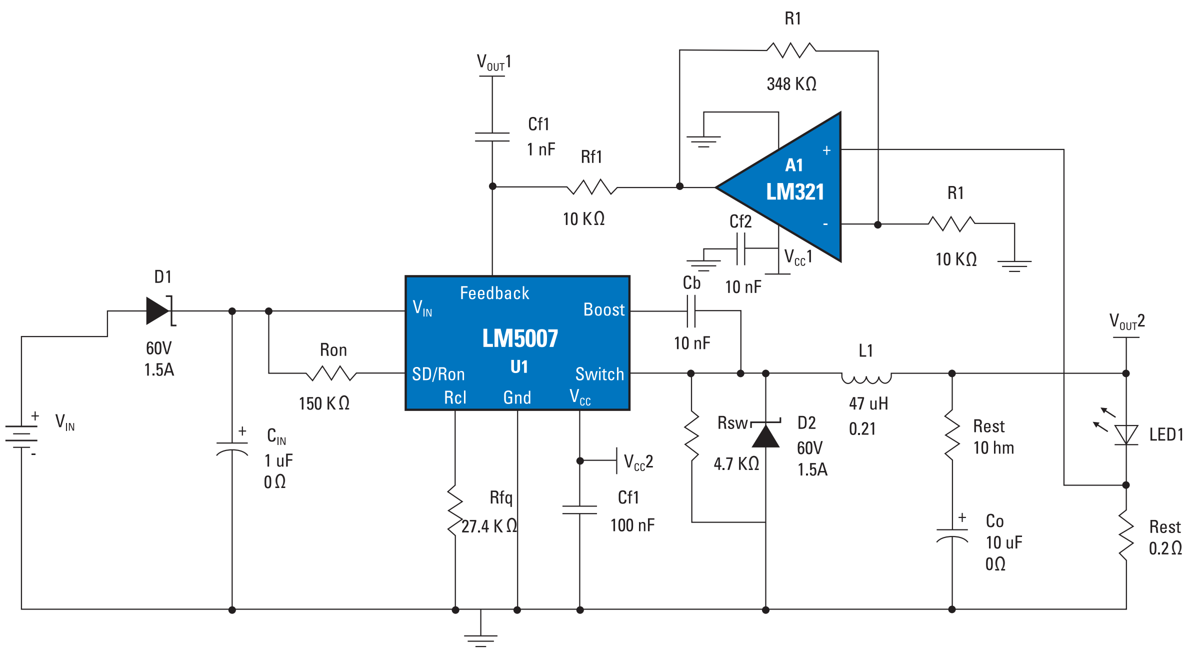
- This circuit is designed to replace a single-filament incandescent bulb in an automobile tail light, brake light, turn signal, reverse light, or interior light (dome light, map light).
- The basic design is a buck current regulator that is capable of providing 350 mA constant current for powering one to two 1W LED from the input voltage of 9V to 40V.
- It is suitable for standard passenger cars and trucks with 8V to 16V batteries as well as freight trucks, tow trucks, fork lifts, and other vehicles that use a double lead-acid battery system (16V to 32V).

Specification:

Inputs	Output #1
V_{IN} Min = 9.0V	V_{OUT1} = 2.3V (typ)
V_{IN} Max = 40.0V	I_{OUT1} = 0.35A

Theory of Operation

- It uses the LM5007MM, a MSOP-8 package buck switcher with an internal 0.7A N-FET switch, to step down the input voltage from 9V to 40V to the required LED voltage of 2.3V (typ).
- With an LED present, as the output voltage ramps to approximately 2.3V, the LED will turn on causing current to flow through R_{set}.
- The voltage across R_{set} is amplified by a factor of 35X by the SOT-5 LM321MF and the gain resistors Rf and Ri. This produces a voltage of 2.45V at the junction of Rf and Rff when 350 mA flows through the LED. The 2.45 volts regulates the LED current at a constant value by the LM5007 internal feedback comparator.
- The LM5007 can withstand inputs voltages of up to 75V. This circuit does not need additional protection from 'load dump' events of up to 75V.
- The brightness of the LED can be dimmed with a PWM input by placing a signal-level NFET from the RON pin to ground and driving the gate with the PWM signal.



LM5010 – High-Volume Buck Switching Regulator Driving 1 High-Brightness LED, 300 or 900 mA

Description:

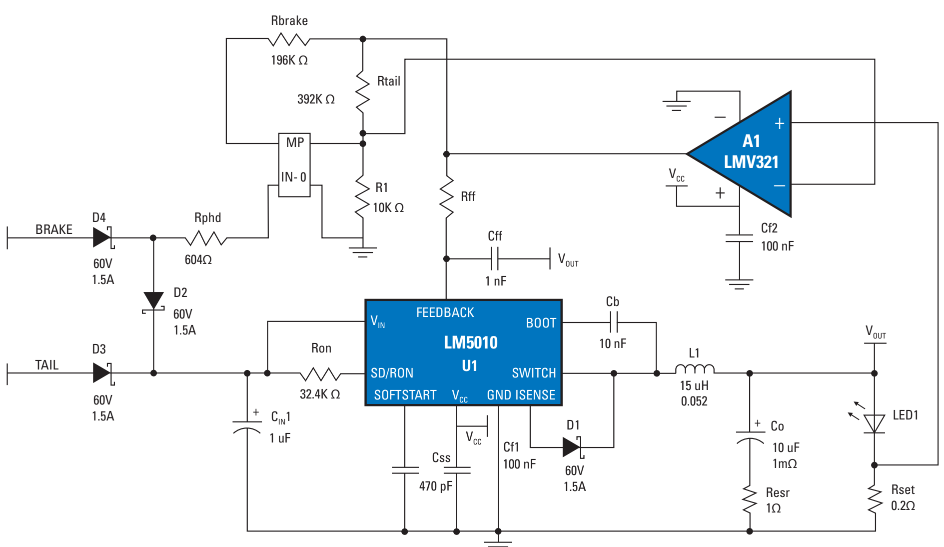
- This circuit is designed to replace a dual-filament incandescent bulb in a combined brake/tail light for automotive use.
- The basic design is a buck current regulator that is capable of providing up to 900 mA constant current.
- When power is applied to the 'Tail' input the current in the LED is regulated to 300 mA. When power is applied to the 'Brake' input or both inputs simultaneously, the current in the LED increases to 900 mA.
- The 'Brake' and 'Tail' input voltage can vary between 8V and 40V. This makes the circuit suitable for standard passenger cars and trucks with 8V to 16V batteries as well as freight trucks, tow trucks, fork lifts, and other vehicles that use a double lead-acid battery system, or 16V to 32V.

Specification:

Inputs	Output #1
V_{IN} Min = 8.0V	V_{OUT1} = 2.5V (typ)
V_{IN} Max = 40.0V	I_{OUT1} = 0.9A

Theory of Operation

- It uses the LM5010MH, a TSSOP-14EP package buck switcher with an internal 1A N-FET switch, to step down the input voltage from 8V to 40V to the required LED voltage of 2.5V (typ).
- When power is applied to the 'Tail' input, the voltage across the Rset is amplified by a factor of 39x by the SOT LM321MF and the gain resistor Rtail and Ri. And the amplification gain is equal to Rtail/Ri. The current LED is regulated to 300 mA.
- When power is applied to the 'Brake' input or both input simultaneously, the photoMOS is turned on. The amplification gain from the voltage across the Rset is reduced to 13x, which is determined by (Rbrake // Rtail) / Ri. Thus, the current in the LED increases to 900 mA.
- Diodes D3 and D4 provide reverse battery protection, and D2 ensures that a 'Brake' input supercedes a 'Tail' input.
- The LM5010 can withstand inputs voltages of up to 75V. This circuit does not need additional protection from 'load dump' events up to 75V.
- The brightness of the LED can be dimmed with a PWM input by placing a signal-level NFET from the RON pin to ground and driving the gate with the PWM signal. This circuit is also compatible with 100 Hz PWM of the input voltage for 'theater dimming' of interior lights.



24V BUS Street Lamp

LM3402 – Constant-Current Buck Regulator Driving 6 InGaN White LEDs, 330 mA

Description:

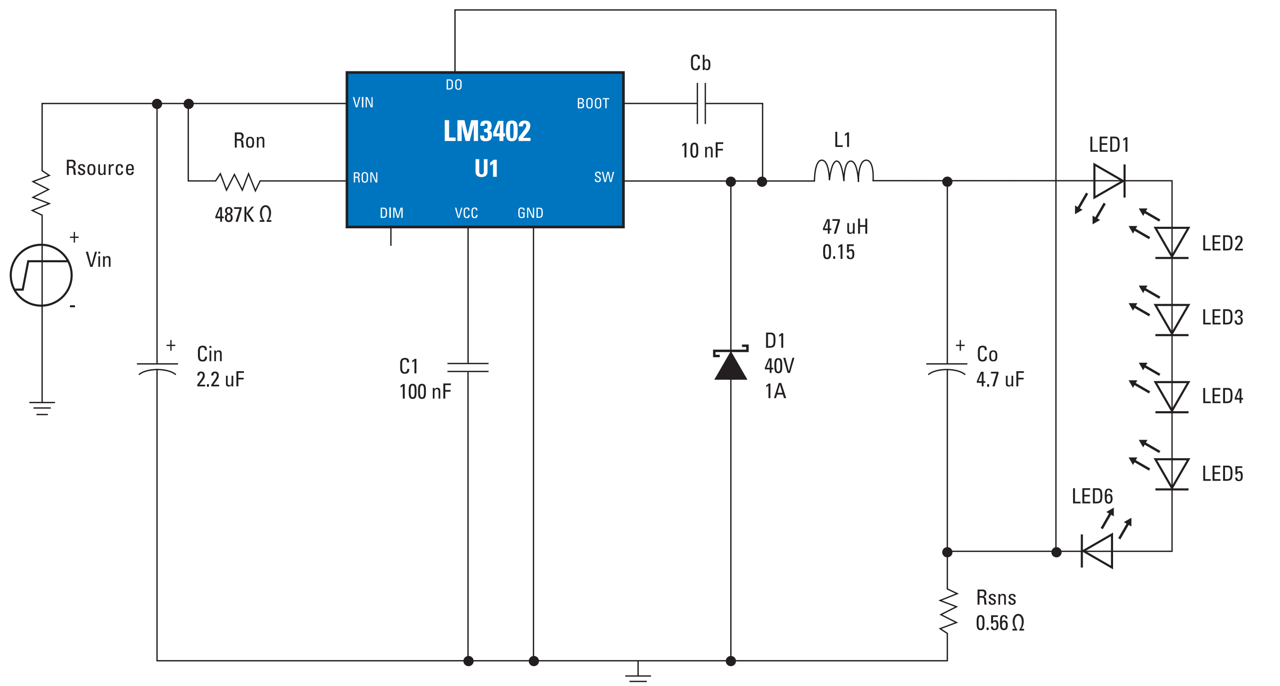
- This design is a basic buck current regulator that is capable of providing constant current of 330 mA.
- This circuit is designed to drive an array of six series-connected InGaN white 1W LEDs (typical V_F 20.4V total) from an input of 24V ±10%.

Specification:

Inputs	Output #1
V_{IN} Min = 21.6V	V_{OUT1} = 20.4V (typ)
V_{IN} Max = 26.4V	I_{OUT1} = 0.33A

Theory of Operation

- It uses the LM3402, a compact and efficient constant-current step down switching regulator with an internal 500 mA N-FET switch, to step down the input voltage from 21.6V to 26.4V to the required six series-connected InGaN white LEDs of typical V_F 20.4V total.
- The low 200 mV feedback voltage greatly reduces the power dissipation of current sense resistor.
- The switching frequency of this application is approximately 350 kHz to provide the smallest component footprint and LED ripple current possible.
- Ripple current in the LED array is 2 mA peak-to-peak, or less than 1% of the average LED current.



LM3402HV – Constant Current Buck Regulator Driving 12 InGaP LEDs, 360 mA

Description:

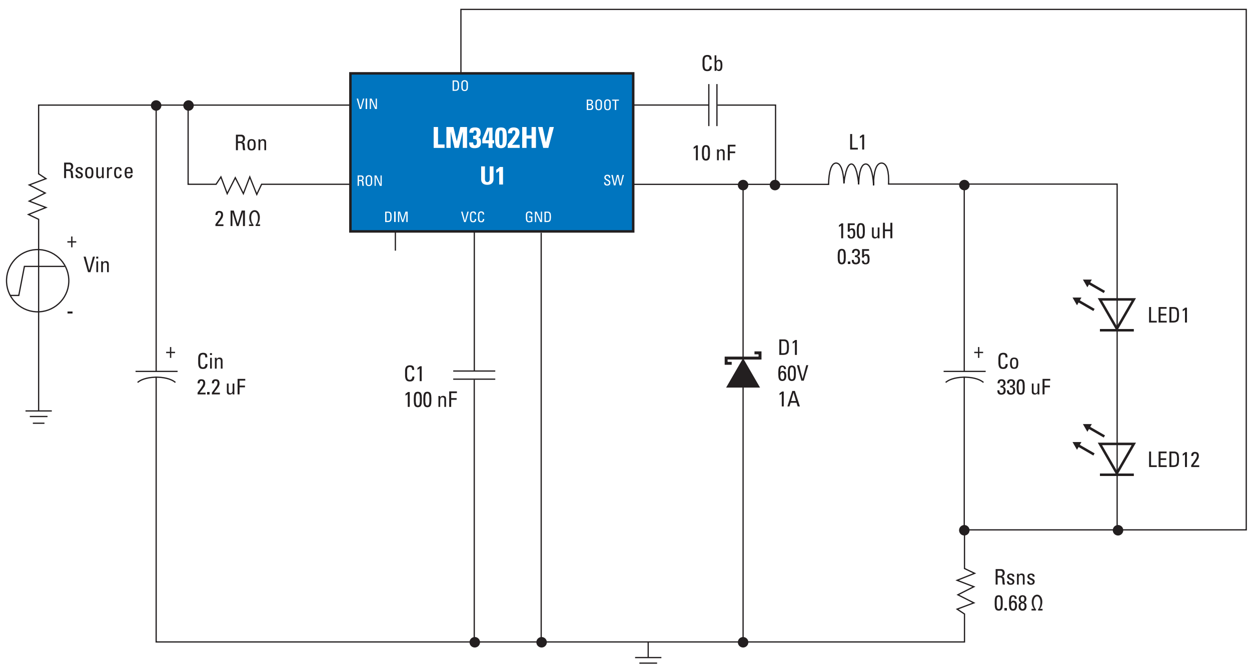
- This design is a basic buck current regulator that is capable of providing constant current of 360 mA.
- This demonstration circuit is designed to drive a string of 12 InGaP 1W LEDs (V_F total about 40.2V) from the input voltage of 47 to 49V.

Specification:

Inputs	Output #1
V_{IN} Min = 47V	V_{OUT1} = 40.2V (typ)
V_{IN} Max = 49V	I_{OUT1} = 0.360A

Theory of Operation

- It uses the LM3402HV, a compact and efficient constant-current step down switching regulator with an internal 500 mA N-FET switch, to step down the input voltage from 47V to 49V to the required twelve series-connected InGaP LEDs of typical V_F 40.2V total.
- The low 200 mV feedback voltage greatly reduces the power dissipation of current sense resistor.
- The switching frequency of this application is approximately 200 kHz, in order to optimize the power efficiency and solution size.
- Ripple current in the LED array is 40 mA peak-to-peak, or less than 12% of the average LED current.



LM3402 – Constant-Current Buck Regulator Driving 1-2 InGaN High-Brightness White LEDs, 335 mA, from 12 VDC Adaptor

Description:

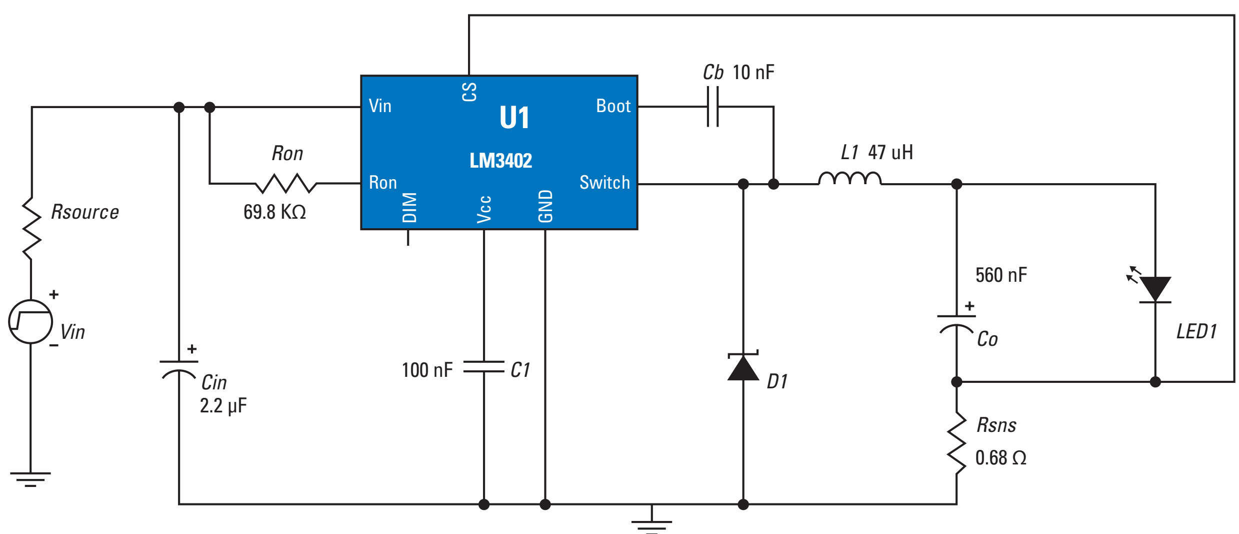
- This design is a buck-current regulator that is capable of providing the constant current of 330 mA.
- The circuit is designed to drive a string of 1 or 2 high-brightness white LEDs from an input of 12V AC/DC adaptor (V_{IN} range: 9 to 16V) for Scanner/MFP Light Source Application.

Specification:

Inputs	Output #1
V_{IN} Min = 9V	V_{OUT1} = 3.5V (typ.)
V_{IN} Max = 16V	I_{OUT1} = 0.335A

Theory of Operation

- It uses a the LM3402, a compact and efficient constant-current step down switching regulator with an internal 500 mA N-FET switch, to step down the input voltage from 9V to 16V to the required single string of 1-2 high-brightness white LEDs as light source for scanner/MFP.
- The low 200 mV feedback voltage greatly reduces the power dissipation of current sense resistor.
- The switching frequency of this application is approximately 400 kHz to optimize the solution size and power conversion efficiency, with a peak-to-peak ripple current of 100 mA or less.



LM3402 – Constant-Current Buck Regulator Driving a Multiple Strings Array of 6 Series Connected InGaN White LEDs, 330 mA, from 24 VDC Adaptor

Description:

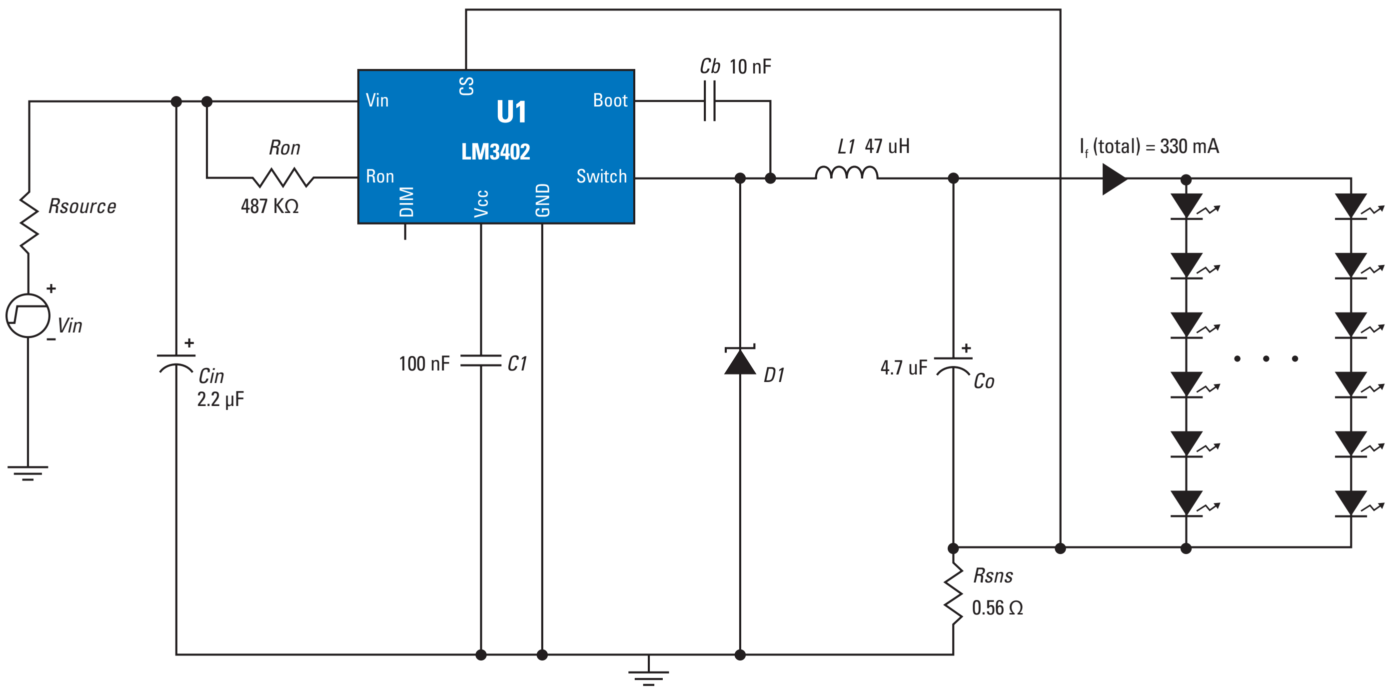
- This design is a buck current regulator that is capable of providing the constant current of total 330 mA.
- This circuit is designed to drive multiple stings of six series-connected LEDs from 24V output AC/DC adaptor for Scanner/MFP Light Source Application.

Specification:

Inputs	Output #1
V_{IN} Min = 21.6V	V_{OUT1} = 20.4V (typ)
V_{IN} Max = 26.4V	I_{OUT1} = 0.33A

Theory of Operation

- It uses the LM3402, a compact and efficient constant-current step down switching regulator with an internal 500 mA N-FET switch, to step down the input voltage from 24V ±10% to the required multiple string LED arrays as light source for scanner/MFP.
- The low 200 mV feedback voltage greatly reduces the power dissipation of current sense resistor.
- The switching frequency of this application is approximately 350 kHz to optimize the solution size and power conversion efficiency,
- The total ripple current in the LED array is 2 mA_{P-P}, or less than 1% of the average LED current.



Notes: This design provides a simple solution to drive multiple strings of LED arrays. To balance the current of each LED string, binning of V_F may be required.

LM3402 – Constant-Current Buck Regulator Driving 1 InGaN LED, 350 mA

Description:

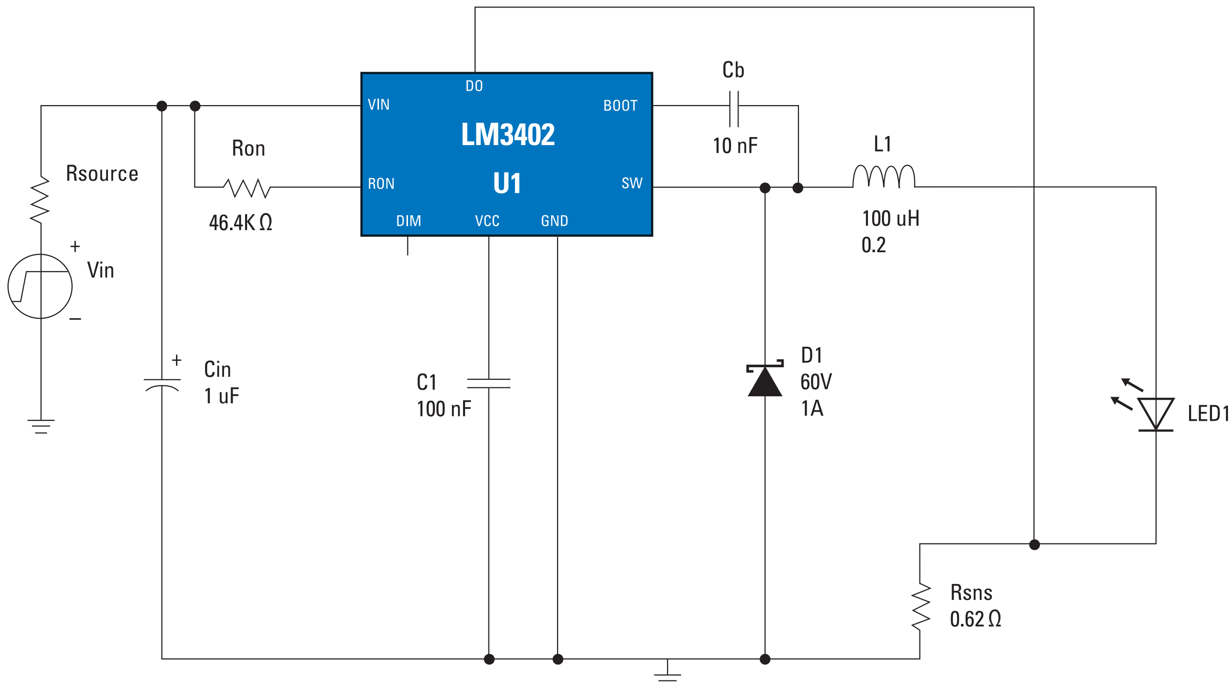
- This design is a basic buck current regulator that is capable of providing constant current of 350 mA.
- This circuit has been designed to drive a InGaN white, blue or green 1W LED (typ.V_F of 3.5V) from the very wide input range of 6V to 42V.

Specification:

Inputs	Output #1
V_{IN} Min = 6V	V_{OUT1} = 3.5V (typ)
V_{IN} Max = 42V	I_{OUT1} = 0.350A

Theory of Operation

- It uses the LM3402, a compact and efficient constant-current step down switching regulator with an internal 500 mA N-FET switch, to step down the very wide input voltage from 6V to 42V to a InGaN white, blue or green LED of typical 3.5V.
- The low 200 mV feedback voltage greatly reduces the power dissipation of current sense resistor.
- The switching frequency of this application is 500 kHz ±10% within the whole input range, to optimize solution size and power efficiency.
- When powered from a 24V ±5% input, the circuit will maintain the average LED current to within 10% of 350 mA. The ripple current will not exceed 70 mA $_{P-P}$.



LM3402 – Constant-Current Buck Regulator Driving 3 InGaP LEDs, 350 mA

Description:

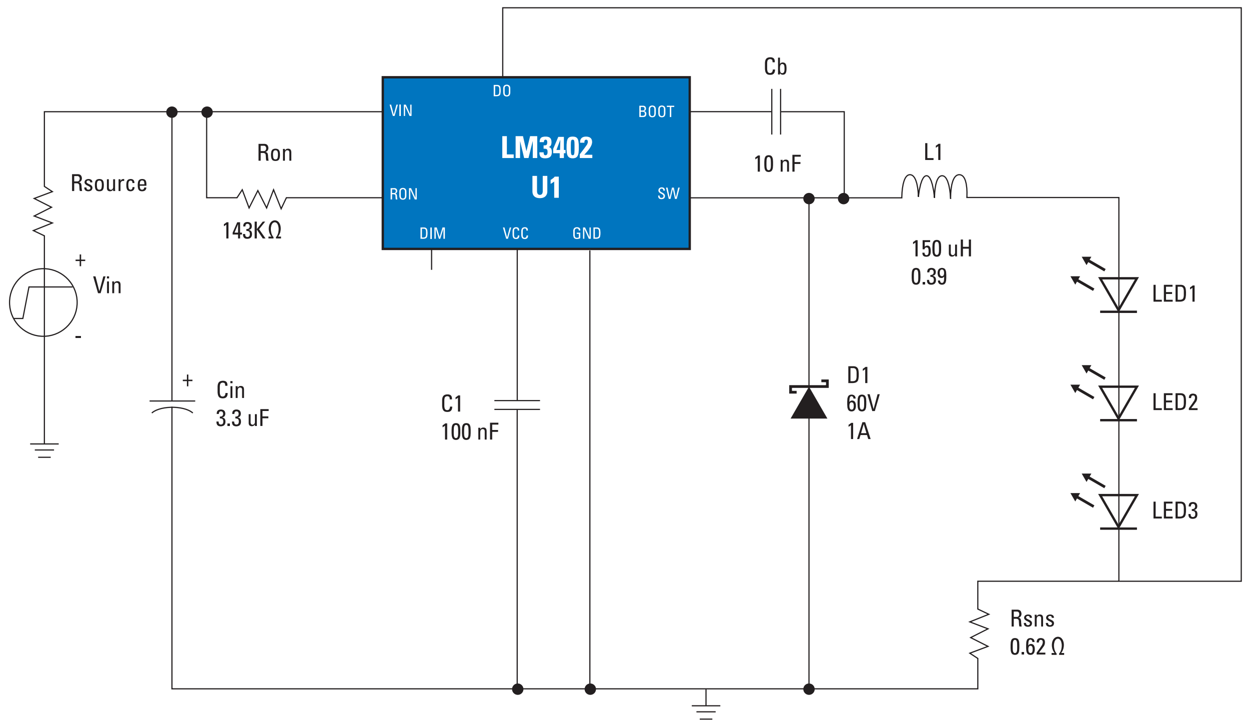
- This design is a basic buck current regulator that is capable of providing constant current of 350 mA.
- This circuit has been designed to drive a string of three series connected 1W InGaP LEDs (total V_O = 10.7V) operated from the wide input range of 14V to 42V.

Specification:

Inputs	Output #1
V_{IN} Min = 14V	V_{OUT1} = 10.7V (typ)
V_{IN} Max = 42V	I_{OUT1} = 0.350A

Theory of Operation

- It uses the LM3402, a compact and efficient constant-current step down switching regulator with an internal 500 mA N-FET switch, to step down the wide input voltage from 14V to 42V to the required three series-connected InGaP LEDs of typical V_F 10.7V total.
- The low 200 mV feedback voltage greatly reduces the power dissipation of current sense resistor.
- The switching frequency of this application is approximately 700 kHz at 24 V_{IN} to minimize the total board size. The ripple current of LED array is 140 mA or less.
- In expectation of fast PWM dimming requirements there is no output capacitor used in this design.



LM3402HV – Constant-Current Buck Regulator Driving 1 InGaN LED, 350 mA

Description:

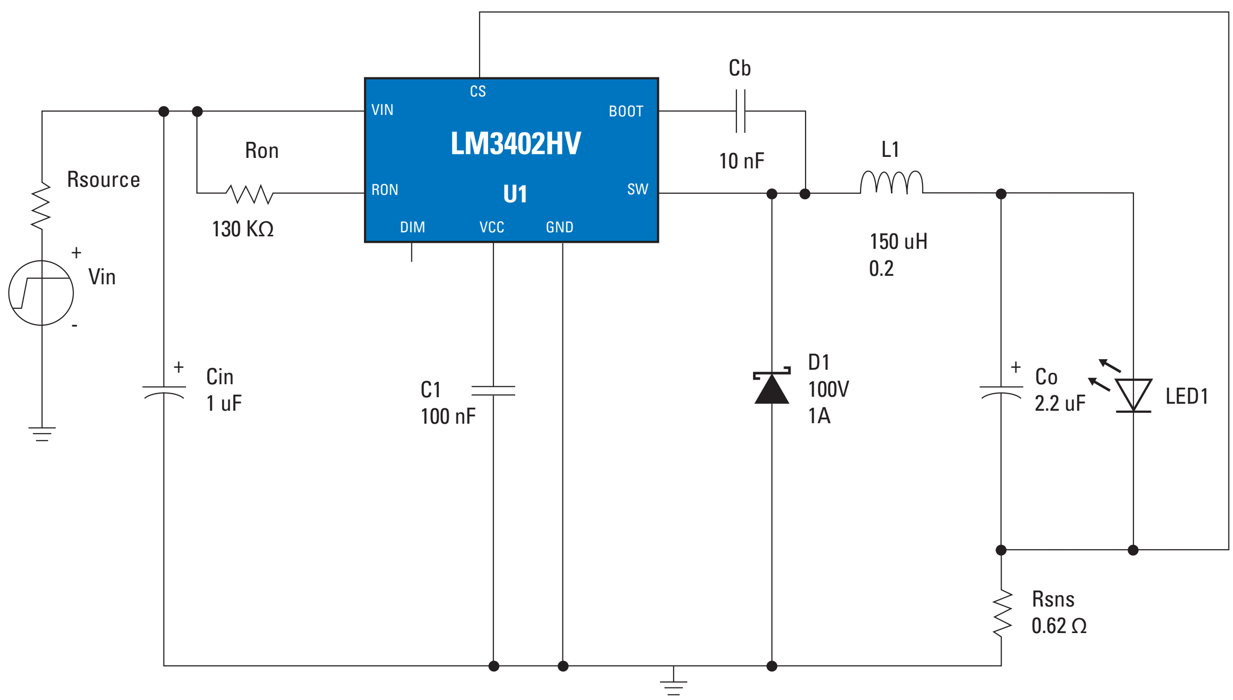
- This design is a basic buck current regulator that is capable of providing constant current of 350 mA.
- This circuit has been designed to drive a 1W InGaN white, blue, or green LED (typ. V_F of 3.5V) operated from the ultra wide input range of 6V to 75V.

Specification:

Inputs	Output #1
V_{IN} Min = 6V	V_{OUT1} = 3.5V (typ.)
V_{IN} Max = 75V	I_{OUT1} = 0.350A

Theory of Operation

- It uses the LM3402HV, a compact and efficient constant-current step down switching regulator with an internal 500 mA N-FET switch, to step down the wide input voltage from 6V to 75V to a InGaN white, blue, or green LED of typical 3.5V.
- The low 200 mV feedback voltage greatly reduces the power dissipation of current sense resistor.
- The switching frequency of this application is 250 kHz ±10% within the whole input range, in order to optimize the solution size and power efficiency.
- When powered from a 48V ±5% input the circuit will maintain the average LED current to within 10% of 350 mA. The ripple current will not exceed 70 mA $_{P-P}$.



Light Matters Part 1: *The ABCs of LEDs*

— By Sameh Sarhan & Chris Richardson, Applications Engineers

Introduction

Light and lighting represent basic and crucial elements in the life of humankind. The pursuit of new lighting sources has been a trend of our civilization. This pursuit is generally driven by technological advancements, needs, challenges, and, sometimes, by luxury. With limited resources, the push towards energy conservation has come to be a mandate, not a choice. Therefore, our world's current challenge is how to balance between the needs of our modern lifestyle and the necessity to 'go green'. When it comes to lighting, it is quite easy to imagine the impact of globally improving the efficiency of lighting sources by 10%. But what if it could be improved by 1000%? The use of newly enhanced Light Emitting Diodes (LEDs) as lighting sources has the potential to achieve these efficiency improvements while maintaining outstanding performance and reliability that supersede many of the currently used sources. Part One of this two part series sheds some light on the basics of LEDs physical structure, colors, efficiency, applications, and drivers.

Anatomy

The physical anatomy of LEDs resembles p-n junction diodes. As in p-n junctions, the electrons and the holes flow towards the junction when a positive differential voltage is applied between the anode (p-side), and cathode (n-side). Once an electron is recombined with a hole, it releases energy. Depending on the physical properties of the p-n junction materials, the released energy can be non-radiative, as in normal diode materials, or may produce optical emissions in the form of photons with LED materials. For an LED, the wavelength of the emitted light (its color) depends on the band gap characteristics of its p-n junction material. Performance-wise, LED materials have relatively low-reverse breakdown voltages since they have relatively low-band gaps.

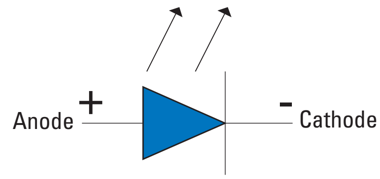
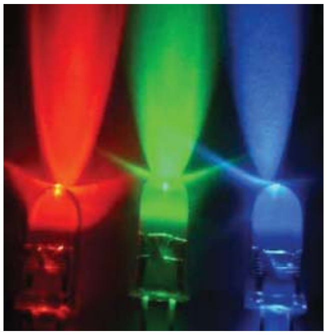


Figure 1: LED Symbol

Colors

Red LEDs were the first to become commercially available in late 1960s, and, as one acquaintance put it: "A dark cave was needed to see the light". Despite the low-light output, they were commonly used in seven segment displays. Thanks to the advancements in material science, nowadays LEDs are commercially available in a variety of colors with some of them having light outputs that would blind you if you stared directly at them. (Please do not try that at home!)

My favorite color, blue, became widely available a few years ago. Mixing blue LEDs with red and green LEDs produces white light (think triad pixel). This technique of generating white light provides a large color gamut, dynamic light tuning, and excellent color rendering (CRI), which is well suited for high-end backlighting applications. A simpler and more economical way of producing white light is to use blue LEDs and a phosphor coating that converts some of the blue light to yellow. The yellow light stimulates the red and green receptors of the eye, therefore, mixing the blue and yellow lights gives the appearance of white. This scheme can provide good CRI but the LED's light output may suffer from inconsistent color temperatures due to manufacturing discrepancies and varying thicknesses in the phosphor coating layer.



Wavelength (nm)	Color Name	Fwd Voltage (V_f at 20 ma)	LED Dye Material
940	Infrared	1.5	GaAIAs/GaAs – Gallium Aluminum Arsenide/Gallium Arsenide
635	High Eff. Red	2	GaAsP/GaP – Gallium Arsenic Phosphide / Gallium Phosphide
570	Super Lime Green	2	InGaAIP – Indium Gallium Aluminum Phosphide
430	Ultra Blue	3.8	SiC/GaN – Silicon Carbide / Gallium Nitride
8000K	Cool White	3.6	SiC/GaN – Silicon Carbide / Gallium Nitride

Figure 2: LED's Color Chart for the Basic Colors

Efficiency

High efficiency has been the buzz word for LED-based light sources. When it comes to lighting, efficiency is defined as the light output per unit power. Thus, in the metric system, it is measured as lumens (lm) per watt (W). Recently some LED manufactures introduced LEDs with promised efficiencies hitting the 150 lm/W mark. In comparison, incandescent comes at 15 lm/W, and fluorescent provides 70 lm/W. So could LEDs put incandescent and fluorescent out of business any time soon? Maybe, but, unfortunately some of these LED's efficiency numbers are subject to specmanship. Here is the problem: the LED inefficiency has to do more with the fact that a considerable portion of the produced light is reflected at the surface of the packing material back into the LED die. This reflected light is likely to be absorbed by the semiconductor material and turned into heat. Utilizing anti-reflection coating and minimizing the reflection angles by using a half-sphere package with the LED placed at the center reduce the amount of reflected light and improve efficiency. However, these techniques are subject to manufacturing variations and may require high premiums to ensure a consistent performance. Otherwise, you can always opt out to specmanship to show off! In a nut shell, there is a rapidly-increasing adoption of LEDs by the electronics industry, but the change is far from complete.

Applications

There are many factors which make LEDs eye-catching for high-performance modern electronics. For example, their higher light output per watt is well suited for portable applications as it extends the battery life. On the other hand, LEDs' fast turn-on/turn-off characteristics fit perfectly with automotive tail lights needs, especially the brake lights, since it improves safety by providing drivers more response time. Using RGB LEDs in backlighting complies with RoHS standards, since LEDs do not contain lead or mercury. LED lighting facilitates a full-spectrum light source with larger color gamut. LEDs have an exceptionally long life span which enables their use in applications where long term reliability is highly desirable, such as traffic lights. Machine vision systems require a focused, bright, and homogeneous light source – LEDs are a great match. LEDs, with their simple-to-implement dynamic light-tuning, would also allow you to set the light in your living room to green when you need to relax and to red when it's time for bullfighting.

Drivers

LEDs are inherently current-driven devices since their brightness varies with their forward current, I_f. Depending on the color as well as the forward current, the LEDs' forward voltage drop, V_F, varies as well. Thus, driving LEDs with a constant current is essential to achieve the desired color and brightness level. An LED driver scheme can be as simple as a voltage source and a ballast resistor ***(Figure 3A)***. This solution works best for narrow-input range, low-current applications in which the LED's forward voltage drop is slightly below the input supply voltage. Variations in the input supply voltage or the LED forward voltage drop will increase the LED current and, therefore, the light intensity and the color will shift. Linear regulators can be used to provide tighter LED current control in small step-down ratio applications ***(Figure 3B)***. In the case of low-current step-up requirements, switching capacitor circuits can be utilized ***(Figure 3C)***.

For wide-input range, high-current applications, simple driver schemes such as those mentioned above will yield high power dissipation and poor efficiency. For example, a linear regulator based LED driver yields 70% efficiency when supplying 1A from a 5V input source to a typical white InGaN LED (V_F= 3.5V). Under the same operating conditions, the driver's efficiency will drop to approximately 30% when the input voltage increases to12V. In addition to degrading the overall performance of an LED based application, such poor efficiencies would require impractical thermal management schemes.

Consequently, more efficient and relatively more complex solutions such as switching regulators would be needed ***(Figure 3D)***. Switching regulators process power by interrupting the power flow and controlling the conversion duty cycle which results in pulsating current and voltage. They can be configured in isolated and non-isolated configurations to realize voltage or current step-down (buck), step-up (boost) or both (buck-boost) functions.

In general, a switching-regulator topology is selected based on a trade-off between cost and desired performance at a given power conversion requirement. On the other hand, in order to properly drive LEDs, the switching regulators should be configured as constant current sources.

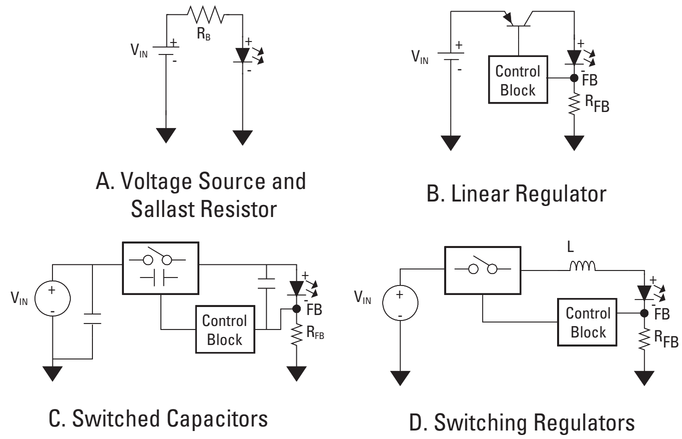


Figure 3: Simplified LED Drivers Schemes

Switching Regulators

To improve the conversion efficiency, switching regulators interrupt the power flow while controlling the conversion duty cycle to program the desired output voltage or output current. Interrupting the power flow results in pulsating current and voltage and therefore it necessitates the use of energy storage elements (inductors and/or capacitors) to filter these pulsating waveforms. Contrary to linear regulators, switching regulators can be configured in different arrangements to realize voltage or current step-down (buck), step-up (boost) or both (buck-boost) functions. They are also capable of achieving high conversion efficiencies across wide input/output range. Replacing the linear regulator with a buck-based LED driver in the previous example yields 95% to 98% efficiency across 5V to 12V input range. The configuration flexibility and the efficiency improvements of switching regulators come at the expense of higher noise generation caused by the periodic switching events, as well as higher premiums and reduced reliability due to their perceived complexity. Utilizing switching regulators to drive constant current LEDs favors regulator topologies that can be simply configured as a constant-current source. The selected topology should also combine high performance with minimum component-count to increase the driver's reliability and to reduce cost. It should also facilitate the use of various dimming techniques to take advantage of the LEDs dynamic light tuning characteristic. Fortunately, the most basic step-down (buck) switching topology enjoys all these characteristics, making it the regulator of choice to drive LEDs whenever possible.

Constant-Current Power Stage

Switching regulators are most commonly known as voltage regulators. ***Figure 4A*** illustrates a basic constant-voltage buck regulator. The buck controller maintains a constant output voltage as the line voltage changes by varying the operating duty cycle (D) or the switching frequency. The desired output voltage set point is programmed using the following equation:

$$V_O = V_{FB}\,\frac{R_{FB1} + R_{FB2}}{R_{FB1}}$$

Eq1

The inductor, L, is selected to set the peak-to-peak current ripple, DI_{PP}, while the capacitor, Co, is selected to program a desired output-voltage ripple and to provide output-voltage hold-up under load transients. The average inductor current in a buck converter is equal to the load current, and, therefore, the load current can be programmed by controlling the peak-to-peak inductor-current ripple. This significantly simplifies the conversion of a constant-voltage source into a constant-current source. ***Figure 4B*** illustrates a basic constant-current buck regulator. Similarly, constant-current buck regulators provide line regulation by adjusting the conversion duty cycle or the switching frequency, and the LED current, I_F, is programmed using the following equation:

$$I_F = \frac{V_{FB}}{R_{FB}}$$

Eq2

Setting the LED current, I_F, requires the proper sensing of the inductor current. Theoretically, multiple current sense schemes such as MOSFET R_{dson} sensing and inductor DCR sensing can be used. However, practically, the current sense precision of some of these would not meet the required LED current set point accuracy (5% to 15% for HBLED). Directly sensing I_F through an inline resistor, R_{FB}, yields the needed precision, but may lead to excessive power dissipation in the current sense resistor. Lowering the feedback voltage, V_{FB}, allows the use of lower resistance value for the same I_F (Eq2), which minimizes losses. Newly-released dedicated LED drivers generally offer reference voltages (feedback voltages) within the range of 50 mV to 200 mV.

Uniquely, constant-current buck-driven regulators can be configured without output capacitance. The use of the output capacitor, Co, in these regulators is limited to AC current filtering since they inherently do not experience load transients and have continuous output currents. Configuring a constant-current buck regulator without output capacitance substantially increases the converter's output impedance and, in turn, boosts the converter's ability to rapidly change its output voltage so that it can maintain a constant current. As a result, the dimming speed and dimming range of the converter improve significantly. Wide dimming range is a highly demanded feature in applications such as backlighting and machine visions. On the other hand, lacking the output capacitance AC- current-ripple filtering necessitates the use of higher inductance values in order to meet the LED manufactures recommended ripple current (DI_F = ±5% to ±20% of the DC forward current). At the same current rating, higher inductance values would increase the size and cost of the LED driver. Consequently, the use of output capacitors in constant-current buck-based LED drivers is governed by a tradeoff between cost and size on one hand, versus dimming speed and dimming range on the other hand. For example, to drive a single white LED ($V_F \approx$ 3.5V) at 1A with a ripple current, Di_F, of ±5% from an input of 12V at 500 kHz would require a 50 µH inductor with a current rating of 1.1A. However if the inductor ripple-current is allowed to increase to ±30% then the inductance required is less than 10 µH. For the same core material and at approximately the same current rating, a 10 µH inductor will be typically offered at roughly half the size and the cost of a 50 µH inductor. To attain the desired Di_F (±5%) using the 10 µH inductor, the output capacitance required is calculated based on the dynamic resistance, r_D, of the LED, the sense resistance, R_{FB}, and the impedance of the capacitor at the switching frequency, using the following expressions:

$$C_O = \frac{1}{2 \times \pi \times f_{SW} \times (Zc - ESR)}$$

Eq3

Where:

$$Zc = \frac{\Delta I_F}{\Delta I_L - \Delta I_F} \times (R_{FB} + r_D)$$

Eq4

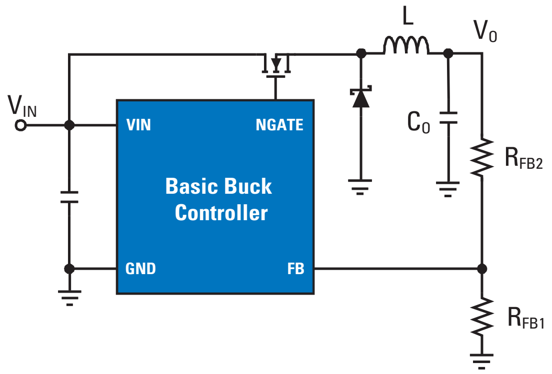


Figure 4A: Basic Step-Down (Buck) Voltage Regulator

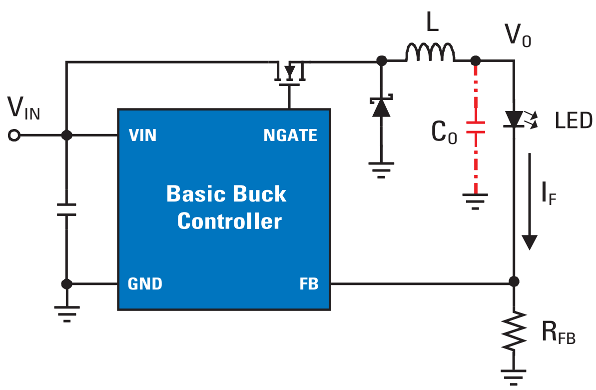


Figure 4B: Basic Step-Down (Buck) Current Regulator

Control-Loop Schemes

Buck-based power stages are well-matched to several control-loop schemes and free of stability limitations such as right-half-plane zeros. They uniquely facilitate the shunt PWM dimming approach in addition to being compatible with other dimming methods. This provides the system designer with configuration flexibility when designing an LED driver for specific requirements. Hysteretic control is well-suited for applications such as light bulbs and traffic lights, in which variable switching frequencies are tolerated or where narrow input voltage range supplies are used. Hysteretic control does not experience control-loop bandwidth restrictions, which eliminates the need for loop compensation because of its inherent stability. Utilizing hysteretic control to drive a buck-based LED driver (***Figure 5A***) greatly simplifies the design as well as reduces the component count, and the cost of the driver. This configuration also yields superior PWM dimming ranges that outperform other buck-based schemes. Using hysteretic buck-based LED drivers with the shunt-dimming approach is well-suited for applications that require ultra-wide dimming ranges at high dimming frequencies and that can tolerate variable switching frequencies. Quasi-hysteretic buck-based LED drivers offer a good compromise between fixed-frequency operation and hysteretic control for applications in which variable switching frequencies may not be desired. The controlled on-time (quasi-hysteretic) buck-based LED driver (***Figure 5B***) employs a control scheme based on a hysteretic comparator and a one-shot on-timer which is used to set a controlled on-time. This controlled on-time is programmed so that it is inversely proportional to the input voltage, and, therefore, it minimizes the switching frequency variations as the line voltage changes. Using this scheme also eliminates the need for control-loop bandwidth limitations, enabling it to achieve wide dimming ranges when used with different dimming configurations. In some cases, as in a number of automotive applications, synchronizing the LED driver(s) to an external clock or to each other may be required to minimize noise interference. Implementing the frequency synchronization feature with the non-clock-based hysteretic and quasi-hysteretic scheme can be challenging. In contrast, this feature can be simply realized in clock-based regulators such as the fixed-frequency buck LED driver shown in ***Figure 5C***. Fixed frequency control generally yields a more complex solution, and it limits the dimming range of the driver regardless of the dimming approach due to its dynamic response limitations.

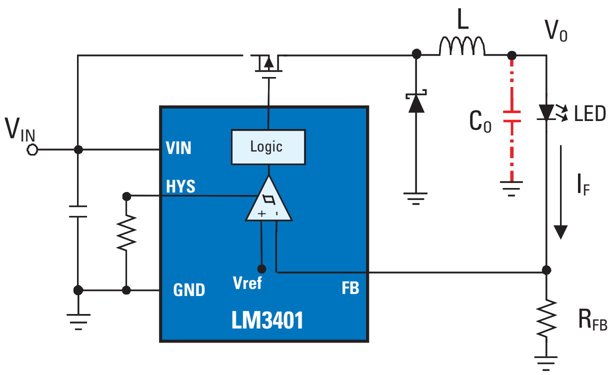


Figure 5A: Basic Hysteretic Buck-Based LED Driver

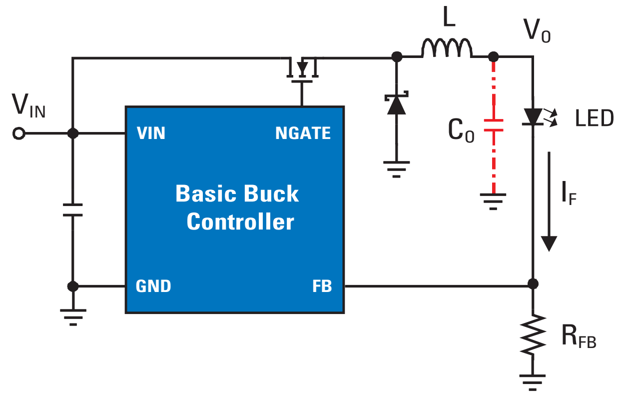


Figure 5B: Basic Controlled On-Time Buck-Based LED Driver

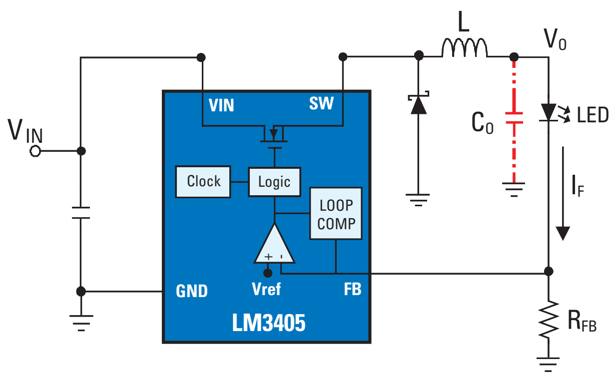


Figure 5C: Basic Fixed-Frequency Buck-Based LED Driver

Conclusion

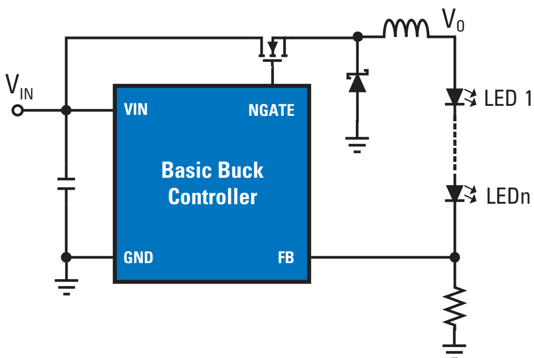
There are many characteristics which make buck-based regulators attractive LED drivers. They are simple to configure as a current source and can be realized with minimum component counts, which simplifies the design process, improves the drivers' reliability, and reduces cost. Buck-based LED drivers also provide configuration flexibility since they are compatible with multiple control schemes. They also allow for high-speed dimming as well as wide dimming ranges since they can be configured without output capacitance and are well-matched to various dimming approaches including shunt dimming. All these features make buck-based (step-down) LED drivers the topology of choice whenever the application permits. Now, the question is: what if the application does not permit? Applications such as residential and commercial lighting require thousands of lumens, creating a need to drive LED strings. The total forward voltage drop of an LED string is equal to the sum of the forward voltage drops of all the LEDs in the string. In some cases, the input voltage range of the system can be lower than the forward voltage drop of the LED string, or it can vary so that sometimes it's lower and sometimes it's higher. These scenarios would require either boost, or buck-boost switching regulators. The next article will discuss, in detail, the challenges of using boost and buck-boost topologies to drive LEDs as well as LED dimming with these schemes.

Light Matters Part 2: *Boosting, Buck-Boosting and Dimming*

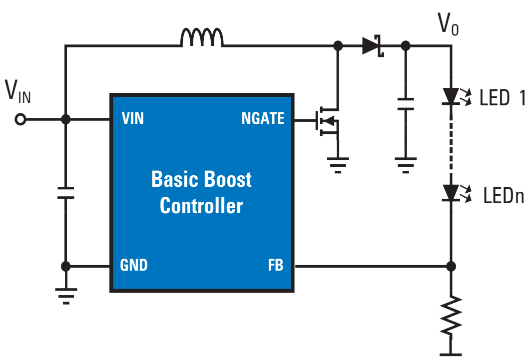
— By Sameh Sarhan & Chris Richardson, Applications Engineers

Introduction

Although the buck is preferred, the boost regulator is finding more use as a direct drive for LEDs as the number of LEDs used in LED lighting applications increases. Designers are targeting large-scale general illumination and systems that require thousands of lumens. Examples include street lighting, residential and commercial lighting, stadium lighting, and decorative or architectural lighting of spaces both interior and exterior.



$V_O = n \times V_F$
$V_O < V_{IN}$



$V_O = n \times V_F$
$V_O > V_{IN}$

Figure 1: Buck and Boost LED Drivers with V_O Calculation

Ideally every LED in every light source would be placed in a single-series chain, ensuring that the same current flows through each device. Even though most general lighting is powered from AC-line voltage, in many cases an intermediate DC bus voltage is used, derived from an AC-DC regulator that takes a universal AC input and provides PFC, isolation, and filtering. Safety standards and electrical codes such as U.L. and C.E. limit the output voltage of the AC-DC power supply that forms the input to an LED driver. Common rails are 12V and 24V, and in some cases 48V. Rarely are these intermediate bus rails higher than 60V, which is the cutoff for DC voltages under U.L. Class 2.

The Challenge of Boost

Boost regulators are more difficult to design and control than buck regulators, regardless of whether the output voltage or the output current is being controlled. Boost regulators require design review at the limits of input voltage to ensure correct design of the inductor, especially the peak current rating. A boost LED driver adds a variable output voltage that influences duty cycle and therefore the inductance and current rating of the main inductor. To prevent inductor saturation, the maximum average and peak currents must be evaluated at both $V_{IN\text{-}MIN}$ and $V_{O\text{-}MAX}$. The more LEDs are placed in series, the greater the gap between $V_{O\text{-}MIN}$ and $V_{O\text{-}MAX}$.

Unlike the buck regulator with its output inductor, the boost converter has a discontinuous output current. An output capacitor is required to keep the output voltage and output current continuous. In a current regulator the output capacitor functions purely as an AC-current filter, and capacitance is made as low as possible while still maintaining the desired LED ripple current.

Another serious challenge for boost converters is the control loop. Most boost converters use peak current mode control, where the impedance of the load has a strong effect on both the DC gain and the low-frequency system pole. For voltage regulators the load impedance is determined by dividing output voltage by output current. LEDs are diodes, with a dynamic resistance. This dynamic resistance can only be determined by plotting the V_F vs. I_F curve and then taking the tangent line to find the slope at the desired forward current. As shown in ***Figure 1***, the current regulator uses the load itself as a feedback divider to close the control loop. This reduces the DC gain by a factor of $(R_{SNS} / (R_{SNS} + r_D))$. It is tempting to compensate a boost LED driver with a simple integrator, sacrificing bandwidth for stability. The reality is that many, if not most LED driver applications require dimming. Whether dimming is done by linear adjustment of I_F (Analog Dimming) or by turning the output on and off at high frequency (Digital, or PWM Dimming) the system requires high bandwidth and fast-transient response just a voltage regulator does.

Further Challenge: Buck-Boost

LEDs for lighting are being adopted much faster than the standards for solid state illumination have developed, and one result is that the input voltages for LED lighting systems often overlap the output voltage (remember, $V_0 = n \times V_F$). Every buck-boost topology stores the entire energy delivered to the load during each cycle in an inductor, transformer or a capacitor, which results in higher peak currents, higher peak voltages or both in the power switches. In particular, evaluation of the converter at the corners of both input voltage and output voltage is necessary because peak switch current occurs at $V_{IN\text{-}MIN}$ and $V_{0\text{-}MAX}$, but peak switch voltage occurs at $V_{IN\text{-}MAX}$ and $V_{0\text{-}MAX}$.

The single inductor buck-boost can be built with the same parts count as a buck regulator or boost regulator, making it attractive from a system cost standpoint. One disadvantage of this topology is that the polarity of V_0 is inverted ***(Figure 2a)*** or regulated with respect to V_{IN} (***Figure 2b)***. Level-shifting or polarity inverting circuitry must be employed. Like the boost converter, they have a discontinuous output current, and require an output capacitor to maintain a continuous LED current. The power MOSFET suffers a peak current of I_{IN} plus I_F and a peak voltage of V_{IN} plus V_0.

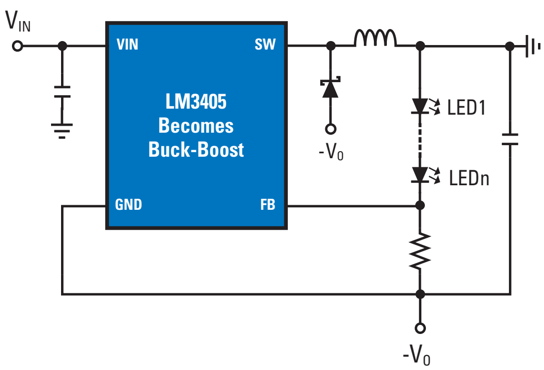


Figure 2a: High-side Buck-Boost

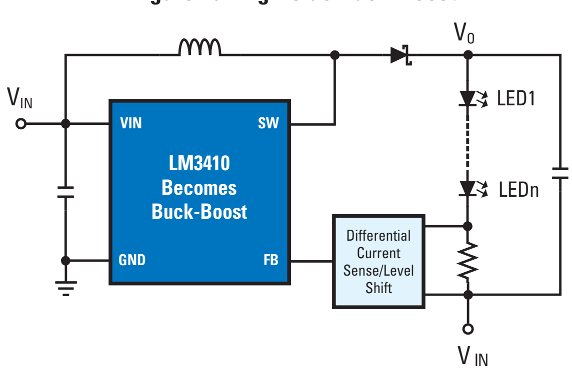


Figure 2b: Low-Side Buck-Boost

The SEPIC converter and Cuk converters both use low-side regulators and have the advantage of a continuous input current due to the input inductor. Their disadvantage lies in needing two inductors, (they can be coupled inductors) and an additional capacitor. The SEPIC requires an output capacitor to maintain a smooth LED current but has a positive V_0, where the Cuk can eliminate the output capacitor but has a negative V_0.

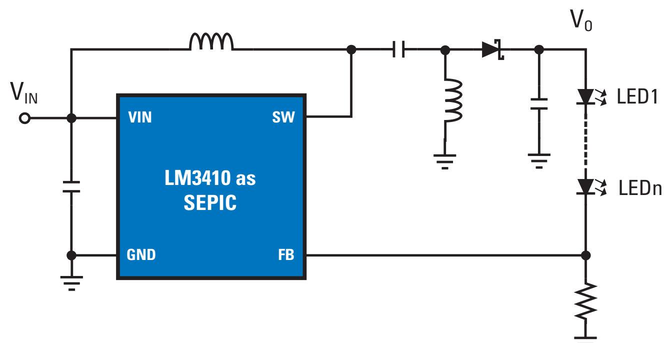


Figure 3: SEPIC LED Driver

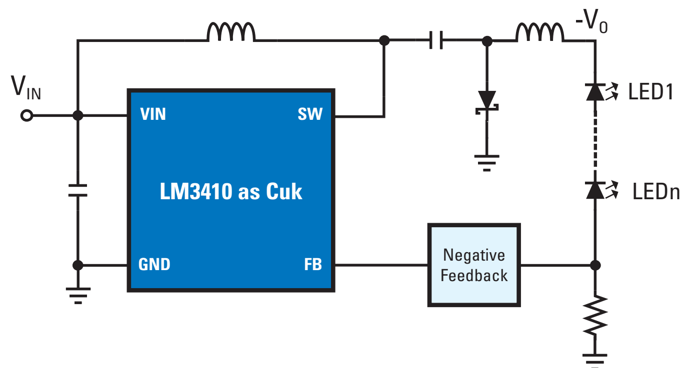


Figure 4: Cuk Regulator

Control LED Light: Dimming

Two main choices for LED light control exist: adjust the LED current linearly (analog dimming) or turning the current on and off at a frequency high enough for the eye to average the light output (digital dimming). Using PWM to set the period and duty cycle is the traditional way to accomplish digital dimming.

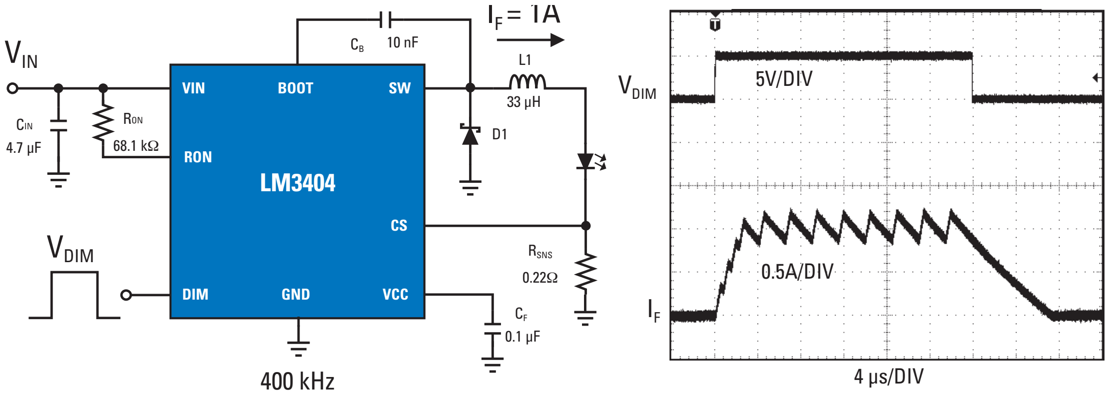


Figure 5: LED Driver Using PWM Dimming with Waveforms

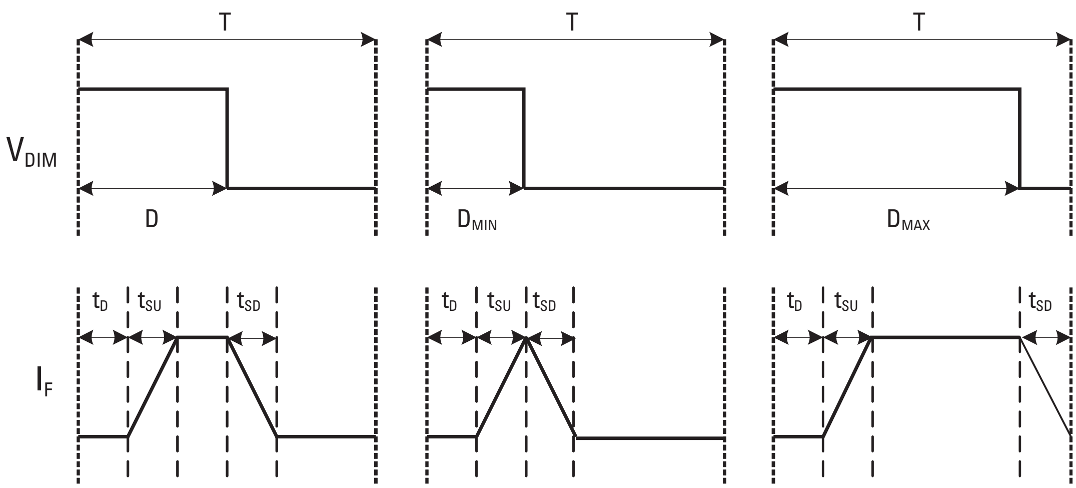
PWM Dimming Preferred

Analog dimming is often simpler to implement, however PWM dimming is used in many designs due to a fundamental property of LEDs: correlated color temperature (white LEDs) or dominant wavelength shifts in proportion to the average drive current. To make white LEDs a blue LED is coated with a broad range phosphor. At low current the light looks more yellow (warm white) but at high current the blue emission dominates and the light becomes more bluish, or cool white. LED manufacturers specify a certain drive current in the electrical characteristics tables of their products where they guarantee the dominant wavelength or CCT. Dimming with PWM ensures that the LEDs emit the color that the lighting designer needs regardless of the intensity.

Analog dimming also presents a challenge to the output current accuracy. Almost every LED driver uses a resistor in series with the output to sense current. The current sense voltage, V_{SNS}, is selected as a compromise between low-power dissipation and high signal-to-noise ratio, SNR. To reduce output current in a closed-loop system, V_{SNS} must be lowered, reducing the output current accuracy in proportion.

Dimming Frequency vs. Contrast Ratio

Every LED driver has a finite response time when responding to a PWM dimming signal. Three types of delay are shown in ***Figure 6***, and the longer these delays are the lower the achievable contrast ratio (a measure of control over lighting intensity).



$$T = \frac{1}{f_{DIM}} \qquad D_{MIN} \; \frac{t_D + t_{SU}}{T} \qquad D_{MAX} = \frac{T - t_{SD}}{T}$$

Figure 6: Dimming Delays

In ***Figure 6***, the quantity t_D represents the propagation delay from when V_{DIM} goes high to when LED current begins to rise. The quantity t_{SU} represents the LED current slew up time, and the quantity t_{SD} represents the slew down time. In general, the lower the dimming frequency, f_{DIM}, the higher contrast ratio, as these fixed delays consume a smaller portion of the dimming period, T_{DIM}. The lower limit for f_{DIM} is approximately 120 Hz, below which the eye no longer blends the pulses into a perceived continuous light. The upper limit is determined by the minimum contrast ratio that is required. Contrast ratio is typically expressed as the inverse of the minimum on-time:

$$CR = 1 / t_{ON\text{-}MIN} : 1$$

$$t_{ON\text{-}MIN} = t_D + t_{SU}$$

Dimming with a Switching Regulator

Switching regulators designed for standard power supplies often have an enable or shutdown pin to which a logic-level PWM signal can be applied, but the associated delays are often quite long. This is because the silicon design emphasizes low shutdown current over response time. Dedicated switching regulations for driving LEDs will do the opposite, keeping their internal control circuits active while the enable pin is logic low to minimize delay.

Optimizing light control with PWM requires minimum slew-up and slew-down delays not only for best contrast ratio, but to minimize the time that the LED spends between 0 and the target level. Where a standard switching regulator will have a soft-start and often a soft-shutdown, dedicated LED drivers do everything within their control to reduce these slew rates. Reducing t_{SU} and t_{SD} involves both the silicon design and the topology of switching regulator that is used.

Buck regulators are superior to all other switching topologies with respect to fast slew rates, for two distinct reasons. First, the buck regulator is the only switching converter that delivers power to the output while the control switch is on. This makes the control loops of buck regulators with voltage-mode or current-mode PWM (not to be confused with the dimming via PWM) faster than the boost regulator or the various buck-boost topologies. Power delivery during the control switch on-time also adapts easily to hysteretic control, which is even faster than the best voltage-mode or current-mode control loops. Second, the buck regulator's inductor is connected to the output during the entire switching cycle. This ensures a continuous output current and means that the output capacitor can be eliminated. Without an output capacitor the buck regulator becomes a true, high impedance current source, capable of slewing the output voltage very quickly. Cuk and zeta converters can claim continuous output inductors, but fall behind when their slower control loops (and lower efficiency) are factored in.

Faster than the Enable Pin

Some applications need high PWM dimming frequency and high contrast ratio, which requires faster slew rates and shorter delay times than even a hysteretic buck without output capacitance can provide. The PWM dimming frequency must often be pushed to beyond the audio band, to 25 kHz or more. Total rise and fall times for the LED current, including propagations delays, must be reduced to the nanosecond range.

Starting with a fast buck regulator with no output capacitor, the delays in turning the output current on and off come from the IC's propagation delay and the physical properties of the output inductor. The best way to bypass both is by using a power switch in parallel to the LED chain, shown in Figure 7. To turn the LEDs off, the drive current is shunted through the switch, which is typically an N-MOSFET. The IC continues to operate and the inductor current continues to flow. Some power is wasted while the LEDs are off, but the output voltage drops to equal the current sense voltage during this time.

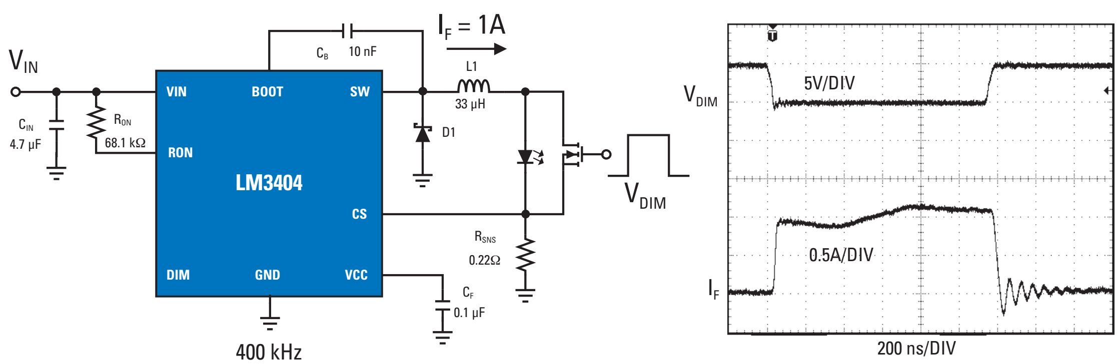


Figure 7: Shunt FET Circuit with Waveforms

Dimming with a shunt FET causes rapid shifts in the output voltage, to which the IC's control loop must respond in an attempt to keep the output current constant. As with logic-pin dimming, the faster the control loop, the better the response, and again buck regulators with hysteretic control provide the best response.

Fast PWM with Boost and Buck-Boost

Neither the boost regulator nor any of the buck-boost topologies are well suited to PWM dimming. Their slower control loops and mandatory output capacitors (except for Cuk) make logic pin dimming much slower than bucks. Trying to dim the output of a boost with parallel FETs will cause an input short circuit, and will cause runaway input inductor current in SEPIC or Cuk. A two-stage system that uses boost and then a buck regulator as the second, LED driving stage is one possibility. When space and cost do not permit this approach, the next best choice is a series switch, shown in ***Figure 8***. Series FET dimming is difficult to achieve without a dedicated LED driver IC because interruption of the LED current also disconnects the feedback to the control loop, which causes the output voltage to rise uncontrollably.

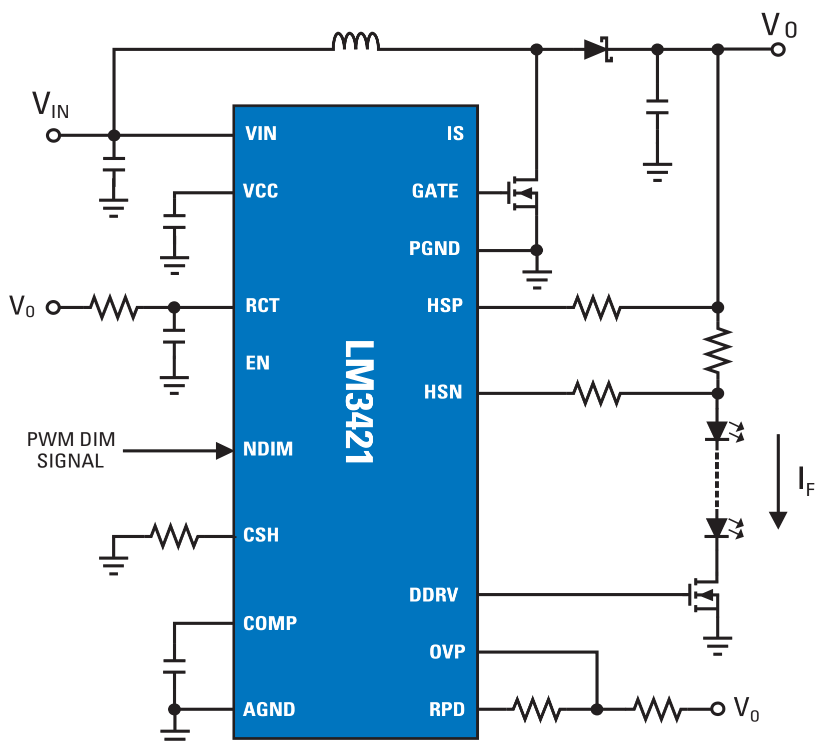


Figure 8: Boost Regulator with Series DIM Switch

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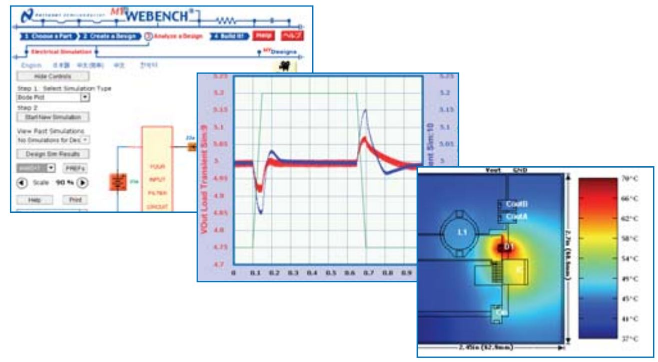

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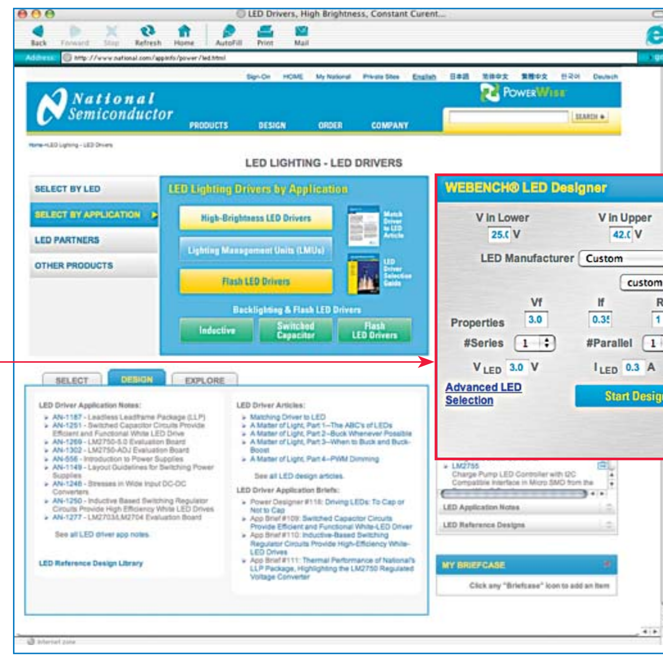

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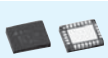

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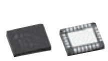

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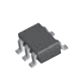

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