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MARGERY CONNER TECHNICAL EDITOR

Solid-state lighting and efficiency from a global perspective

WHAT IS THE WORLD'S APPETITE FOR LIGHT? What if an increase in lighting efficiency does not result in less energy consumption but in more lighting for the same amount of energy? Jeff Tsao, a researcher at Sandia National Labs who studies the technology and economics of lighting, posed this question at the opening session of the Strategies in Light conference last February. Tsao examined data on the worldwide consumption of artificial light for the past 300 years, which covers the introduction of candle, kerosene, gas, incandescent, and fluorescent/high-intensity-discharge lighting.

Over the past 300 years, the world has spent a constant 0.72% of its GDP (gross domestic product) on artificial lighting. This observation translates in the United States to the equivalent of 17 100W light bulbs turned on per capita, per waking hour. Africa's usage equivalent is one 0.5W light bulb burning for every person's waking hours. (Tsao notes that this 0.5W light consumption is the same as the amount that the citizens of London used in 1850.)

This relationship between GDP and lighting usage accounts for increases in the COE (cost of energy) because COE affects the lighting-usage equation by driving down the GDP. That is, people consume less energy for lighting only if the COE increases or their standard of living in general decreases, not because lighting becomes more efficient. As lighting becomes more efficient—that is, cheaper—then lighting usage increases. This conclusion follows intuitively from knowing that, in general, people consume more as costs go down. So, the move toward LED-based SSL (solid-state lighting) may be an effective strategy for lowering energy consumption, but only if it's paired with an increase in productivity.

COE plays a major role in GDP, but it's not the only factor: Another way to increase GDP is to become more productive. Throughout history, lighting has helped productivity. As lighting technology advanced—from kerosene to gas lamps to electricity—lighting became cleaner, light sources took less time to turn on and off, light-induced heat decreased, and fire hazards decreased. The conclusion Tsao reaches is that efficiency alone does not result in a decrease in energy consumption. An increase in productivity must accompany that efficiency.

Here's a likely conclusion we can draw based on this study: The killer app for LEDs won't be a replacement bulb for 40W home lights because that application won't increase anyone's productivity. Rather, the opportunities for LED lighting will be in applications that have inherent intelligence and can interact with their environments and humans in ways that make both more productive and intelligent.

I discussed Tsao's study in my Feb 22, 2009, *Power-Source* blog (see "LEDs for lighting: Efficiency is not enough," www.edn.com/090409leda). Many readers posted comments, some agreeing and some disagreeing with Tsao's conclusions. Several readers and people at the conference who had heard Tsao's presentation assumed that, by making people more productive, LED lights automatically conserve energy, such as when you network them to automatically turn on and off or dim during premium energy-usage periods. Based on the connection of productivity to GDP, however, it seems more likely that Tsao was referring to LED systems that directly and significantly affect human work output.

"Think … about the undeveloped world not currently on grid electricity, [often] using kerosene lamps and hardly consuming light at all [compared with] the developed world," he says. "Their productivity would be increased in so many ways … if they had access to more light." Clearly, Tsao believes that a direct connection exists between access to clean, safe, efficient light and quality of life.

Undoubtedly, the affluent, light-rich world would benefit from the coming shift to SSL. But that benefit will be nothing compared with families and workshops in undeveloped countries, who will no longer have to use dangerous, expensive kerosene lighting to finish a day's work or start a night's schoolwork.

If you're interested in how LEDs will acquire intelligence and enhance productivity, consider attending *EDN*'s free Designing with LEDs workshop, which will take place on April 30, 2009, at the Hyatt Regency in Santa Clara, CA. Go to www.edn.com/leds for more information.

BY JEFF PERRY, NATIONAL SEMICONDUCTOR

A fail-safe approach to LEDs

Choose the right high-brightness LED and protect it from overtemperature conditions.

Spurred by the increasing cost of energy and concerns about climate change, governments and industry are pushing for higher-efficiency lighting. HB LEDs (high-brightness light-emitting diodes) provide an excellent option due to their high efficiency and long lifetime. At the same time, LED technology is undergoing a period of rapid change and innovation.

Fortunately, online tools for LED selection and implementation make it easier to choose an LED and an LED driver. But, even with these tools, the user should have an understanding of the parameters affecting LED selection.

The first step is choosing a color for the LED. Colored LEDs are characterized by their dominant wavelength and are available in wavelengths from UV (ultraviolet) to IR (infrared). Manufacturers specify white LEDs by their color temperature, with warm-white LEDs, often used for room lighting, in the 2800 to 3500K range. An ordinary tungsten-filament light bulb offers about 3000K. Also available are cool-white LEDs in the 6300 to 7500K area and white LEDs in the mid-range of 3600 to 6200K.

HOW BRIGHT SHOULD IT BE?

Luminous flux, in units of lumens, is the usual measurement for the brightness of LEDs. It indicates the amount of light emitted in the spectrum to which the human eye is sensitive. **Table 1** shows typical luminous-flux values for some light sources.

HB LEDs typically have luminous-flux values of less than 100 lumens, although this figure is climbing rapidly. So designs typically combine LEDs into arrays to achieve higher brightness values. You can arrange multiple LEDs in parallel strings using one current-control driver, but doing so can lead to differences in brightness in the strings due to the slight variance in each LED's forward voltage and thus current in each string. Therefore, it is preferable to use LEDs in series for consistent brightness and color. However, the series voltage gets higher with more LEDs, affecting which driver topology you can use: buck or boost.

Also keep in mind that LEDs are directional in nature, according to the viewing angle, or the point at which the brightness falls to 50% intensity. In directional applications, the actual brightness you perceive will be higher than a point source of light with a spherical emission pattern. Conversely, if you desire a spherical emission pattern, you must design the array accordingly.

A measure of efficiency of lighting elements is luminous efficacy, which is measured in units of lumens per watt. With the explosion of LED R&D, parts with values of 75 lumens/watt are readily available, and LEDs with 115 lumens/watt are new

TABLE 1 TYPICAL FLUX VALUES FOR COMMON LIGHT SOURCES

Type	Brightness (lumens)
40W tungsten bulb	500
100W tungsten bulb	1500
25W compact fluorescent	1500
55W halogen auto headlight	1500
35W high-intensity-discharge auto headlight	3250
150W projector bulb	5000
180W low-pressure sodium streetlight	27,000

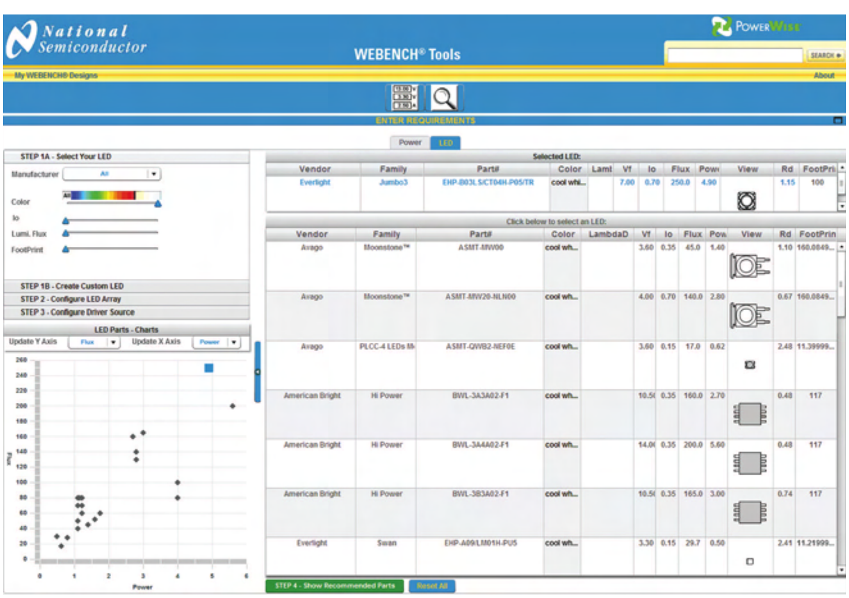

FIGURE 1 Comparing luminous flux with power aids in selecting the proper HB LED (courtesy National Semiconductor).

to the market. Tungsten-filament bulbs offer about 17 lumens/watt, CFLs (compact fluorescent lamps) offer 60 lumens/watt, and low-pressure sodium streetlights offer 100 to 200 lumens/watt (**Figure** 1).

The forward voltage of an LED is a characteristic of the manufacturing process; yellow/orange/red LEDs are in the 2 to 3V range, and blue/green/white LEDs are in the 3 to 4V range. The current through the LED controls the brightness and affects the color. Therefore, LEDs run in a constant-current mode. High-brightness LEDs typically come in currents of 0.35, 0.7, 1, 1.4A, and up. Also, consider the footprint and height of the LED. You must make provisions for heat sinking, which becomes vital in high-current applications. Cost is another critical parameter.

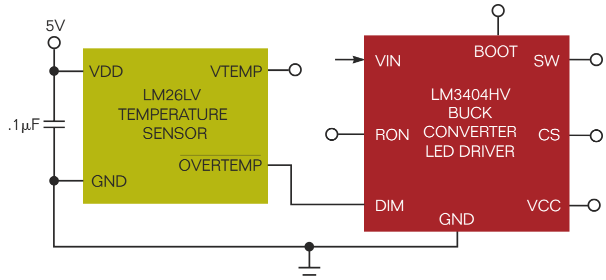

FIGURE 2 AN LM26LV silicon temperature sensor can sense an HB LED's overtemperature condition and throttle back the LM3404HV LED driver.

TEMPERATURE CONTROL FOR LEDs

Why do we need temperature control and monitoring for LEDs if they are supposed to be so efficient? Although LEDs are more efficient than tungsten-filament bulbs, they still generate a lot of heat. Incandescent lights generate heat that largely leaves the system as IR radiation. On the other hand, LEDs generate heat in the diode-semiconductor structure in addition to photons. This heat is not part of the radiated spectrum, and it must exit the system through conduction and convection.

If LEDs become hot, a number of issues arise. The brightness of LEDs decreases markedly with temperature. Also, the color of LEDs changes with temperature, which can lead to problems in applications that require consistent color integrity, such as RGB (red/green/blue)-generated white light. Electrical characteristics, such as the forward voltage of the LEDs, drift with temperature—a consideration when designing the driver circuitry. This change can also be an issue if the LEDs share current in parallel configurations. Constant exposure to high junction temperatures accelerates the degradation of LEDs and reduces their life and reliability. Thus, it is essential to design the system so it runs within the temperature specification of the LEDs. You normally accomplish this task using heat sinks, such as large copper areas on the PCB (printed-circuit board). You can also use attached-fin heat sinks, thermally enhanced/metal PCBs to mount the LEDs, or both. Forced airflow is also an option.

However, if an unusual event, such as extraordinary weather-related heat or the failure of a heat sink, occurs, you can implement a fail-safe mechanism. Most buck-topology LED drivers have thermal shutdown. Boost-topology drivers protect themselves but not the load when they shut down, so they require a crowbar circuit or other protection for LEDs. In any case, the LED temperature may be higher than that of the driver, and the LEDs thus require a temperature-sensor and monitoring circuit for fail-safe protection. This temperature-sensor circuit can reduce or turn off the current to the LEDs, turn on a cooling fan, or provide an alert mechanism to the user or maintenance personnel.

In general, temperature-sensor accuracy needs to provide enough margin to be able to detect an overtemperature problem but not trigger a false alarm under normal operating temperatures. For example, if a system is normally operating at as much as 80°C and you want to detect a fault condition at no more than 100°C, a temperature-sensor system with ±2°C accuracy set to trip at 98°C should be fine, but one with ±10°C accuracy set to trip at 90°C would be marginal.

Discrete temperature sensors appropriate for LEDs include thermistors, which change resistance as the temperature changes. Thermistors are inexpensive and have high sensitivity but are nonlinear and require initial calibration. They are available in the desired temperature range of 50 to 150°C. Another choice is a thermocouple. The voltage of these sensors changes as the temperature changes; they also generate a current, so they may not require a power source. They are less sensitive than thermistors but good enough for LED use. They come in a range of temperatures, well beyond what LEDs require, and see wide use in other applications. They cost more than thermistors. Both of these sensors require some analog circuitry either to interface with a microcontroller, which then can take action to correct the temperature problem, or to interface directly to the LED driver through a shutdown or dimming pin.

Silicon temperature sensors, which come in ranges of −50 to +150°C, are also useful for LED applications. These inexpensive sensors provide a variety of options, including analog-voltage output, which is proportional to temperature; temperature-triggered on/off output with hysteresis; and fan control.

TEMPERATURE-SENSOR APPLICATION

Figure 2 shows a simple circuit for interfacing a silicon temperature sensor directly to a buck-LED driver. The temperature sensor should be as close as possible to the LEDs. In this circuit, the Overtemperature pin of the temperature sensor is normally high when the temperature is below the specified value, but the pin goes low when the temperature is high, thus shutting off the LED driver through the Dim pin. When using the sensor's hysteresis feature, as the temperature goes back 5°C below the specified value, then the Overtemperature pin goes high, and the LED driver turns back on.

More sophisticated systems can proportionally reduce current to the LEDs without shutting them down as the LED temperature rises above a threshold. Alternatively, they can turn on a fan and increase speed after the LED temperature exceeds the specification. None of these systems are a substitute for good thermal design for the LEDs, but you can use them as a fail-safe shutdown to enhance LED life and reliability when the normal thermal controls fail.

Acknowledgment

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Jeff Perry is the senior manager of the Webench online-design-tools group at National Semiconductor.

BY JOHN BETTEN, TEXAS INSTRUMENTS

Inverting buck-boost converter regulates LED current

When input- and output-voltage ranges overlap and are "dirty" to boot, consider biasing on LEDs with a negative voltage.

Controlling the brightness of LEDs requires a driver that provides a constant, regulated current. To achieve this goal, the driver topology must be able to generate a large enough output voltage to forward bias the LEDs. So, what are your choices when the input- and output-voltage ranges overlap? In one case, the converter may need to step down the input voltage, and, in another, it may need to boost up the output voltage. These situations often arise in applications with wide-ranging "dirty" input-power sources, such as automotive systems. Several topologies work well in this buck or boost roll, such as the SEPIC (single-ended-primary-inductor converter) or a four-switch buck-boost converter. These topologies generally require a large number of components, increasing the materials cost of the design. Although most experts consider these choices acceptable, the converters provide positive output voltages. A negative-output voltage converter, however, can provide an alternative that you should not overlook.

Figure 1 shows the schematic of an inverting buck-boost circuit driving three LEDs in a constant-current configuration. This circuit has several positive attributes. First, it uses a standard buck controller, minimizing cost and facilitating possible system-level reuse. You can easily adapt this circuit to use an integrated FET buck controller or a synchronous-buck topology for improved efficiency. This topology uses the same number of power-stage components as a simple buck converter, thereby realizing the fewest components for a switching regulator and the lowest overall cost compared with other topologies. Because the LED output is light, it may not matter from a system level that the LEDs are biased on with negative rather than positive voltage.

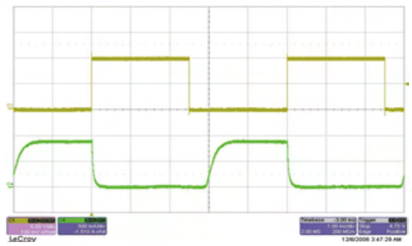

FIGURE 2 Shorting the soft-start capacitor to ground allows the PWM drive (top) to dim the LED by decreasing its current (bottom). For applications that don't require high-speed response or 100% PWM dimming, this method may suffice.

The system regulates LED current by

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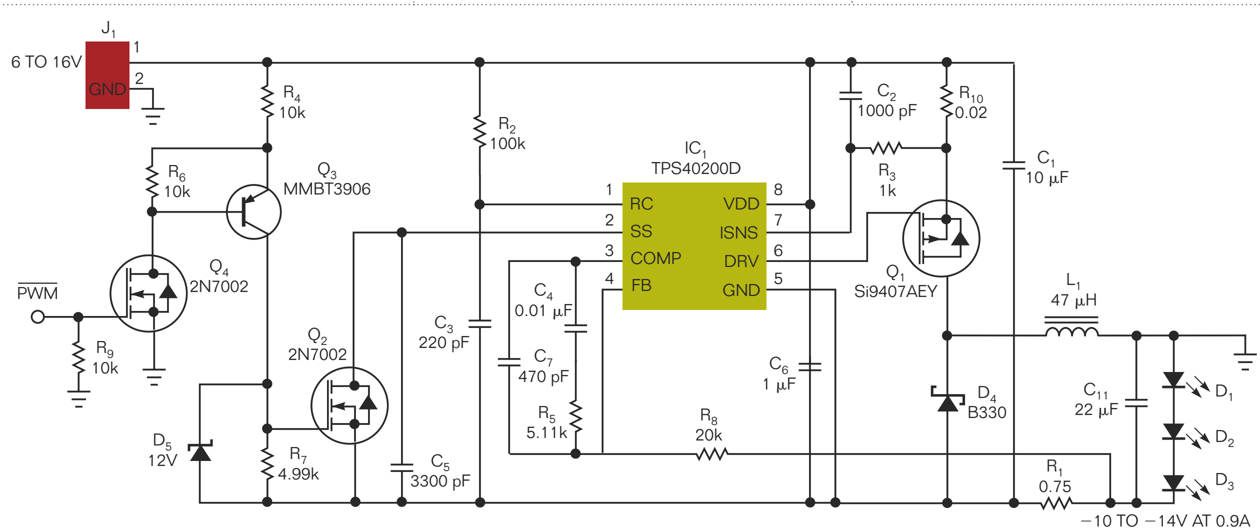
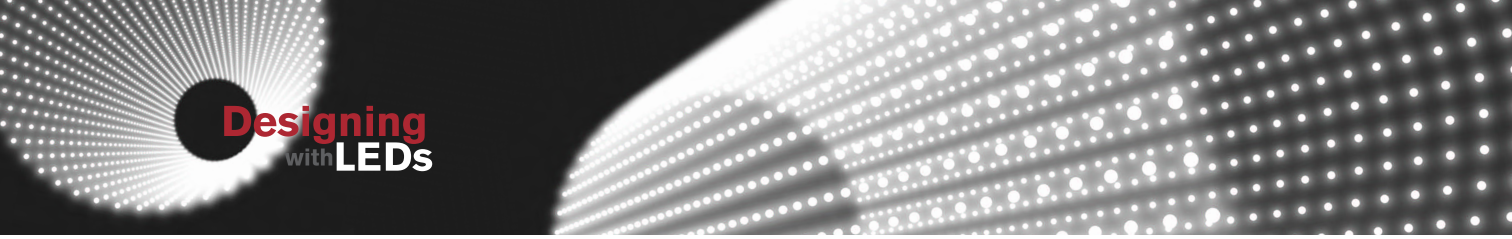


FIGURE 1 This buck-boost circuit regulates a constant LED current with a negative output voltage.



BY SILVESTRO FIMIANI, POWER INTEGRATIONS

Solving the LED-driver challenge for light-bulb replacement

The Department of Energy is offering a prize of as much as $10 million to create the first solid-state replacement for the 60W incandescent light bulb, so you know it's a problem. Here are some suggestions for how to address high-efficiency, power-factor, and phase-dimming-compatibility requirements.

The lighting industry is exploring ways to replace the standard 60W light bulb with a more energy-efficient, HB-LED (high-brightness-light-emitting-diode)-based design. LED lighting offers the prospect of a 10-fold efficiency improvement over incandescent lamps. With a potential lifetime of 100,000 hours, this improvement would virtually eliminate maintenance and replacement costs.

The US government has recognized the potential of LED lighting and intends ultimately to use LED lamps in all government buildings. To provide a stimulus for the development of LED lighting, the US Congress has mandated a prize of as much as $10 million for the first organization or individual to create and validate an LED-based screw-in replacement for the standard Edison-type, 60W incandescent bulb. The new bulb has to contain not only the LED chips, but also the driver circuitry—no easy challenge given the space constraints and potential electrical-noise issues. The lamp must achieve an efficacy of more than 90 lumens per watt, making power-supply performance critical to a successful design.

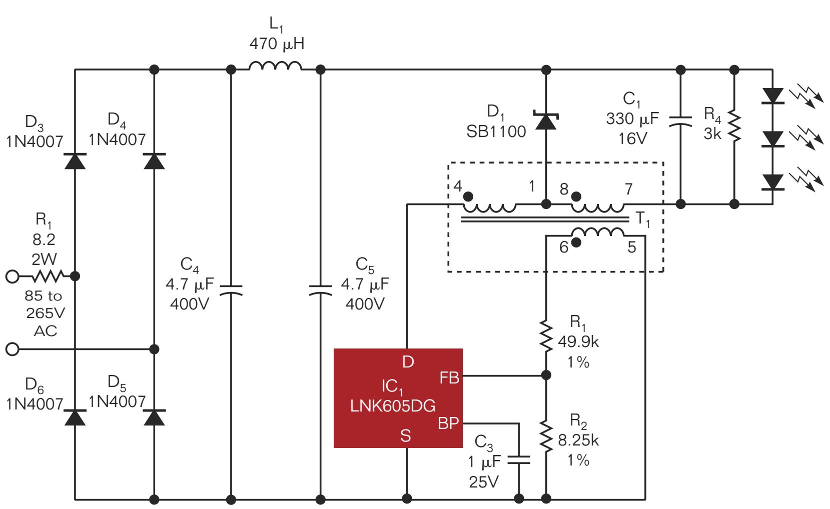


FIGURE 1 Power Integrations based this tapped-buck power supply on the LNK605DG switching IC, which uses just 16 components. This circuit operates over an input-voltage range of 85 to 265V ac, enabling the use of one lamp worldwide.

To provide an even spread of light, an LED lamp typically contains a dozen or more LEDs. The brightness of LEDs is a function of current flow, and LEDs have a typical threshold voltage of 3.4V, with a variation from 2.8 to 4.2V. The LEDs in a lamp connect in series strings, presenting the power supply with a CC (constant-current)-drive requirement across a potentially wide voltage range.

Several companies have recently developed primary-side switch-mode-control configurations, an example of which is the tapped-buck topology (**Figure 1**). The key advantages of the tapped-buck topology are that it lends itself to a smaller PCB (printed-circuit board), a smaller inductor core, and greater efficiency—more than 80% for 4.2W—than an isolated flyback converter. EMI (electromagnetic-interference) filtering is also simpler due to less common-mode noise generation. In the tapped-buck topology, the load connects in series with the inductor—in this case, T_1 windings 1, 2, 3 4, 7, and 8—and the primary switching element, a 700V MOSFET, which the SMPS (switched-mode-power-supply) controller, IC_1, incorporates. When IC_1, a Power Integrations (www.powerint.com) LNK605DG, turns off, the energy in T_1 induces a current to flow in the output winding (pins 7 and 8). The current in the output winding steps up by a factor of the inductor's turns ratio and flows from the output winding, through freewheeling diode D_1, and the load.

IC_1 switches at a rate as high as 88 kHz, minimizing the size requirements of the inductors and capacitors. In CV (constant-voltage) mode, the circuit generates 12V±5% to 350 mA when it switches into CC mode. This operating mode is the normal one for LED loads, and the circuit

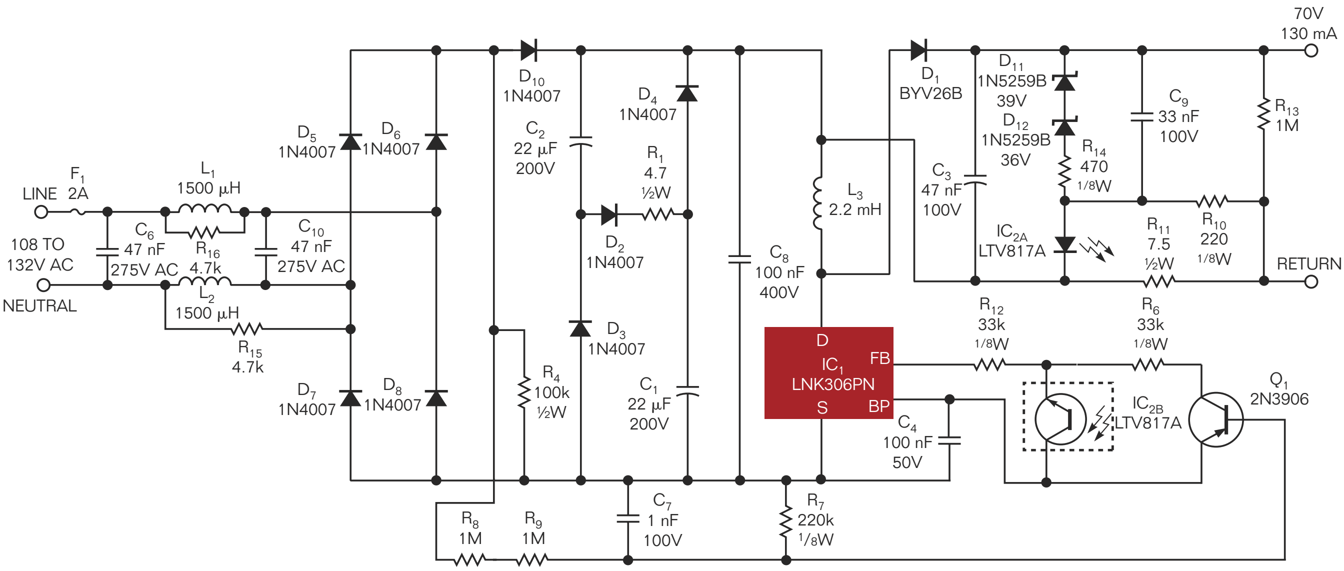


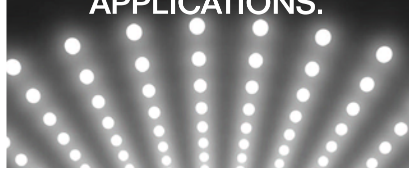
FIGURE 2 This 9W LED driver uses a valley-fill circuit for an improved power factor, which a draft version of the Energy Star requirements for solid-state lighting requires.

maintains 350 mA±10%. The key to this simple design is the control circuitry within IC_1. The circuit implements feedback control using only input from the bias winding (pins 5 and 6) in T_1. It requires no sense resistor to generate the CC output, and it needs neither an optocoupler nor secondary control circuitry. The control method compensates for variations in the inductor and other component tolerances and for input-voltage variations.

At the beginning of each switching cycle, IC_1 switches on, and current ramps up until it reaches IC_1's current limit, when the switch in IC_1 turns off. With IC_1 off, the energy in T_1 induces a current to flow in the output winding, not only maintaining the current through the load, but also stepping it up by means of the turns ratio. Capacitor C_1 filters the load current and removes the switching component. The on/off-control-state machine and switching frequency vary in response to the feedback voltages at the FB input. In CC mode, as the output voltage and, therefore, the flyback voltage across the bias winding increase, the feedback-pin voltage increases. This increase produces a reduction in the switching frequency, thus providing a constant output-current regulation. In CV operation, the controller regulates the output voltage using the on/off-state machine.

The CV characteristic of IC_1 operates at start-up as the IC ramps up to CC mode and ensures output-overvoltage protection. A fault condition can cause the part's die temperature to rise to more than a nominal 142°C, initiating a hysteretic thermal shutdown. The circuit is an efficient and effective approach to powering a plug-in Edison-replacement LED lamp, providing compliance with EMI standard EN (European Norm) 55015 Class B, with 10 dB of margin. At this power level, you can implement the Energy Star requirements for power-factor control using a valley-fill circuit (**Reference** 1 and **Figure 2**). Note that this circuit introduces additional passive components that increase the board size and, more seriously, reduce conversion efficiency.

A PFC CIRCUIT GIVES THE SUPPLY A POWER FACTOR GREATER THAN 0.92, WHICH MEETS THE REQUIREMENTS OF ENERGY STAR SSL FOR COMMERCIAL APPLICATIONS.



Energy Star recently introduced a proposal that SSL (solid-state-lighting) replacement lamps should be dimmable (**Reference** 2). Adding this function would require additional circuitry and would have a negative impact on efficiency. You can add the dimming capability by introducing a circuit to detect the phase of the rising edge that the SCR (silicon-controlled rectifier) generates, but you must carefully perform this task to ensure compliance with power-factor and harmonic-current limits. A buck-boost circuit can meet these requirements. The buck-boost supply provides a CC output as high as 9W at a maximum output voltage of 70V dc from 108 to 132V ac and includes phase-detection logic for use with SCR dimmer controls. A passive-valley-fill PFC (power-factor-correction) circuit gives the supply a power factor greater than 0.92, which meets the requirements of Energy Star SSL for commercial applications. The high-output-voltage design helps to boost efficiency and compensate for additional losses due to the valley-fill circuit. The supply also meets EN 55015B EMI requirements.

In this circuit, switching controller IC_1 uses an on/off control. Current-sense resistor R_{11} generates a voltage across the diode of optocoupler IC_{2A}. This feedback signal goes to IC_1's FB pin through IC_{2B} and R_{12}. D_{11}, D_{12}, and R_{14} clamp the output voltage under no-load conditions to approximately 80V, achieving a CV/CC characteristic. The phase-detection logic takes advantage of the on/off control to use the SCR phase angle to inhibit switching, thereby reducing the load current and accomplishing dimming. D_{10} isolates the line voltage from the bulk capacitors, thus allowing you to obtain conduction-angle information. R_7, R_8, and R_9 form a voltage-divider network. C_7 averages the voltage across R_7. As a dimmer reduces the line voltage, the voltage across C_7 also decreases. This reduction in turn reduces the voltage on the base of Q_1 to less than 5.1V, at which point Q_1 turns on, pushes current into the FB pin, and inhibits switching.

D_2, D_3, and D_4, along with C_1 and C_2, form the valley-fill circuit and provide power-factor correction. The valley-fill circuit shapes the input current to improve the power factor. C_1 and C_2 charge in series as the line voltage rises and discharge in parallel when it falls. Thus, input-current flow remains the same from 30 to 150°C and 210 to 330°C. This continuous current greatly improves the system's THD (total harmonic distortion) and power factor.

These applications illustrate two approaches to implementing an LED replacement for the standard incandescent light bulb. The first example requires few components and produces a universal lamp for all supply voltages. The second application adds a dimmable lamp and perhaps a more compatible replacement for the standard light bulb. Although more complex, it is still capable of better-than-85% efficiency at full load. Alternative approaches to dimming, such as three-wire systems or replacing SCR dimmers with IGBTs (insulated-gate bipolar transistors), offer less compatibility but are more technically elegant and efficient. For further information on power supplies for LED lighting, see **Reference** 3.

References

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2 "Low-Cost Dimmable LED Ballast Using the Valley-Fill Current Shaping Circuit," Power Integrations Inc, www.powerint.com/sites/default/files/PDFFiles/di171.pdf.

3 "LED Driver ICs," Power Integrations Inc, www.powerint.com/applications/led-lighting.

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sensing the voltage across sense resistor R_1 and using it as feedback to the control circuit. For this direct feedback to work properly, you must reference the controller's ground pin to the negative output voltage. Referencing the controller to system ground would require a level-shifting circuit. This "negative ground" places several restrictions on the circuit. The power MOSFET, diode, and controller must have a higher voltage rating than the sum of the input and the output voltage.

Second, external interfacing with the controller, such as enable, requires level-shifting the signal from system ground to controller ground, resulting in additional components. For this reason alone, it is best to eliminate or minimize the use of unnecessary external controls.

Finally, an inverting buck-boost converter places additional voltage and current stresses on the power devices compared with a four-switch buck-boost circuit, reducing relative efficiency. But the stresses are comparable to that of the SEPIC. Even so, this circuit achieved 89% efficiency. You can achieve additional improvements of 2 to 3% by making the circuit fully synchronous.

A simple way to dim the intensity of the LEDs is by rapidly turning the converter on and off via shorting out soft-start capacitor C_5. **Figure** 2 shows the PWM input signal and the actual LED current. This PWM-dimming technique is efficient because the converter is off and consumes little power when the SS pin is shorted. But this method is also relatively slow because the converter must ramp the output current up in a controlled fashion each time it goes on, introducing a nonlinear, finite dead time before the output current rises. This action also reduces the minimum on-time duty cycle to 10 to 20%. In LED applications that do not require high-speed and 100% PWM dimming, this method may suffice.

This inverting buck-boost circuit provides an additional option for driving LEDs. Using a low-cost buck controller and a few parts makes this alternative suitable for more complex topologies.

John Betten is an application engineer and senior member of the technical staff at Texas Instruments and has more than 23 years' worth of ac/dc- and dc/dc-power-conversion-design experience. Betten received his bachelor's degree in electrical engineering from the University of Pittsburgh and is a member of IEEE.