Convert a Buck Regulator into a Smart LED Driver

by Jon Kraft, Applications Engineering Manager, Analog Devices, Inc.

LEDs promise to change the world, and few doubt that they will, but a key limiter to more rapid adoption is the cost of the LED themselves. The cost breakdown of LED luminaires vary, but it is safe to put the cost of the LED at around 25% to 40% of the total luminaire cost. It is projected to remain a significant cost of the total luminaire for many years.
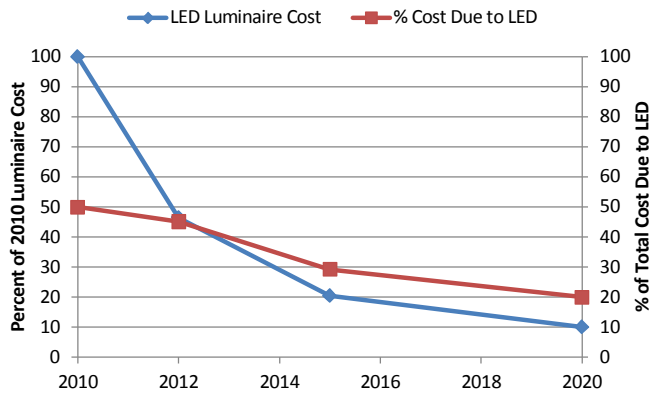

Figure 1. Breakdown of LED Luminaire Costs[1]

One way to reduce the total luminaire cost is to drive an LED at its highest possible current. If driven properly, these LEDs produce a greater lumens/cost.
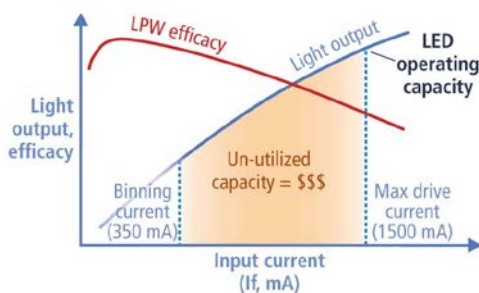

Figure 2. Potentially Under-Utilized Operating Capacity for the Cree XLamp XP-G LED[2]

Doing this requires higher current drivers, and while there are many solutions to drive LEDs at low currents (<500 mA), there are fewer options at higher currents (700 mA to 4.0 A). This is all the more surprising given that the semiconductor world is rich with <4.0 A dc-to-dc solutions. However, the problem is that these dc-to-dc solutions are made to control voltage—not LED current. In this article, we will examine

some easy tricks to take a readily available dc-to-dc buck regulator and transform it into a super smart LED driver.

A buck regulator simply chops up an input voltage, passes it through an LC filter, and gives a stable output. To do this, the buck employs two active elements and two passive elements. The active elements are a switch from the input to the inductor (labeled A in Figure 3) and a switch (or diode) from GND to the inductor (labeled B in Figure 3). The passive elements are the inductor (L) and the output capacitor (C_{OUT}). These form an LC filter, which reduces the ripple created by the active elements. Their arrangement is shown in Figure 3.
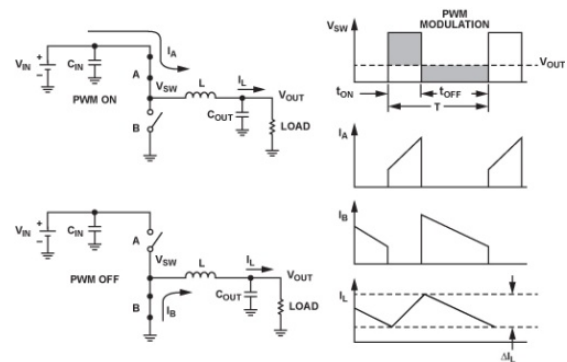

Figure 3. Basic Buck Arrangement[3]

If the switches are internal, we call it a "regulator." Otherwise, it is a "controller." If both switches are power transistors (either MOSFETS or BJTs), then it is "synchronous"; otherwise, it is called "asynchronous." This gives several categories of buck circuits, and each has its own merits and drawbacks. The discussion of which type to use, and all the trade-offs, would be extensive. But in a very general sense, the solution that often times gives an optimal efficiency, BOM count, solution cost, and board area is a synchronous buck regulator. However, synchronous buck regulators that drive high current LEDs (up to 4 A) are few and expensive. So, why not take a standard synchronous buck regulator and modify it to regulate LED current? We will use two examples of recently released general-purpose synchronous buck regulators from Analog Devices: the ADP2441 and the ADP2384.

The ADP2441 is a high efficiency, 36 V input synchronous buck regulator, capable of producing an output current of up to 1.2 A. The ADP2384 is another high efficiency synchronous buck regulator but with an output current of up to 4.0 A and an input voltage up to 20 V. Standard output voltage regulation schematics for both are shown in Figure 4.

For both the ADP2441 and the ADP2384, the output voltage is resistor divided down to the FB pin. This is compared against an internal 600 mV reference and used to generate the proper duty cycle to the switches. In steady state, this FB pin regulates to exactly 600 mV. So, instead of a resistor divider, it is easy to put the LEDs there (Figure 5), with a resistor (R_{SENSE}) in series to set the current.
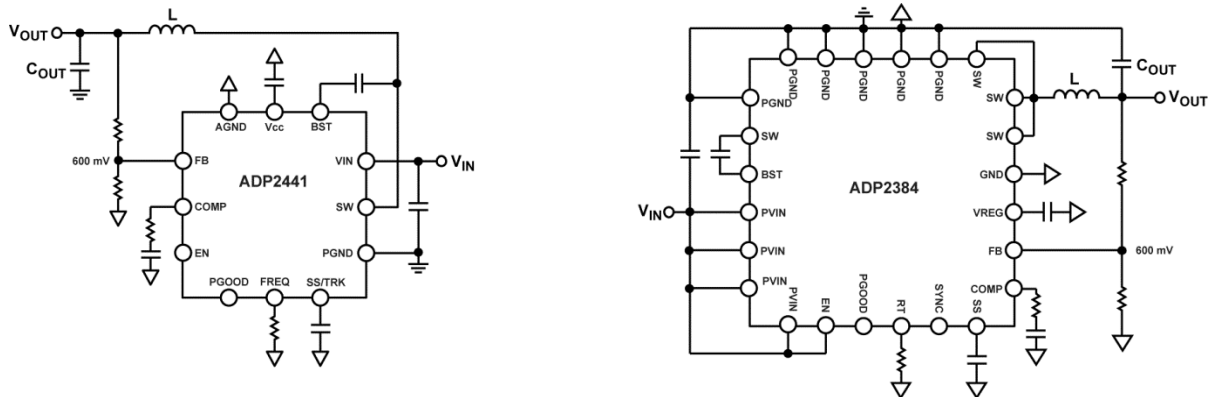

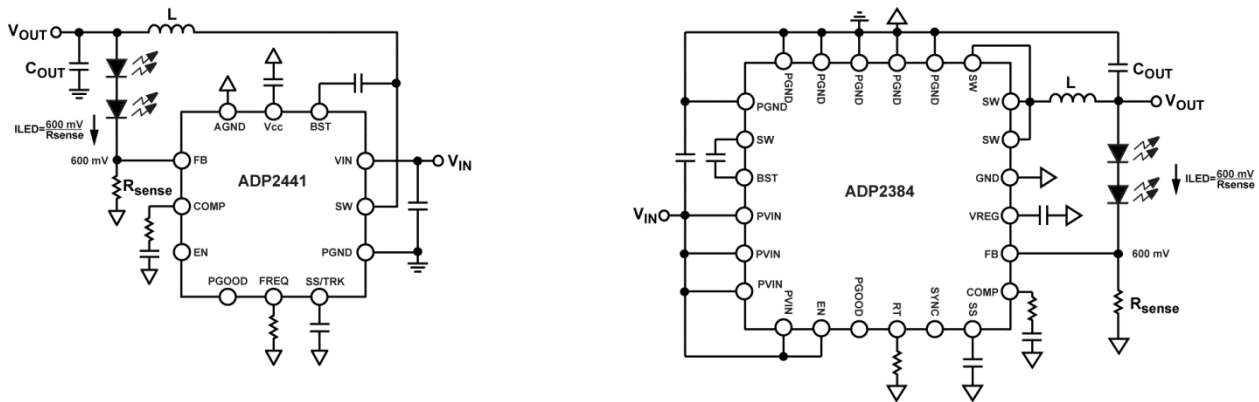*Figure 4. ADP2384 and ADP2441 Schematics for Regulating Output Voltage*

Figure 5. Basic (but Inefficient) LED Driver

Using a precision resistor from FB to GND sets the LED current to ILED = 600 mV/R_{SENSE}. This works nicely, but it produces a lot of power dissipation: P_{DISS} = 600 mV × ILED. For low LED currents, it is not a big issue, but at high LED currents, the impact to efficiency adds significantly to the heat that the luminaire must dissipate (600 mV × 4 A = 2.4 W). Fortunately, there are two tricks we can use to reduce the FB reference voltage for most buck regulators: use the SS/TRK pin or offset the R_{SENSE} voltage.

Many general-purpose buck ICs include a soft start (SS) or tracking (TRK) pin. The SS pin is intended to be used to provide a controlled inductor current at startup, and the TRK pin is intended to have the buck regulator follow an independent voltage. Often times, the pins are combined into one SS/TRK pin. In most cases, the error amplifier will use the minimum of the SS, TRK, and FB reference voltages to change the regulation point. The typical setup is shown in Figure 6.
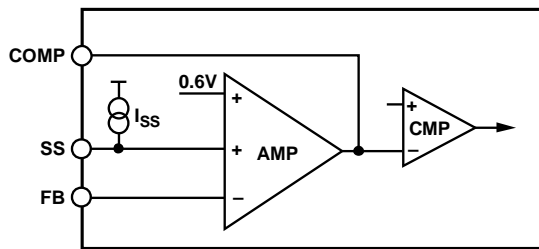
But for our purposes, we want to just set the SS/TRK pin to a fixed voltage and use it as our new FB reference. A resistor divider from a constant voltage to this pin works nicely. Many of these buck regulator ICs include a controlled low voltage output, like the VREG pin on the ADP2384 or the VCC pin of the ADP2441. For greater accuracy, a simple 2-terminal precision reference like the ADR5040 can be used. Either way, a resistor divider from the supply to the SS/TRK pin forms the new reference. Setting the resistor divider to give a SS/TRK voltage around 100 mV to 200 mV generally offers the best compromise between power dissipation and LED current accuracy. Another benefit to setting your own feedback reference voltage is that any sense resistor values (which are found in standard values) can be easily accommodated. This prevents the expense and inaccuracy of paralleling multiple R_{SENSE} resistors to set the LED current.

Figure 6. Soft Start and/or Tracking Pin Operation (ADP2384 Shown)
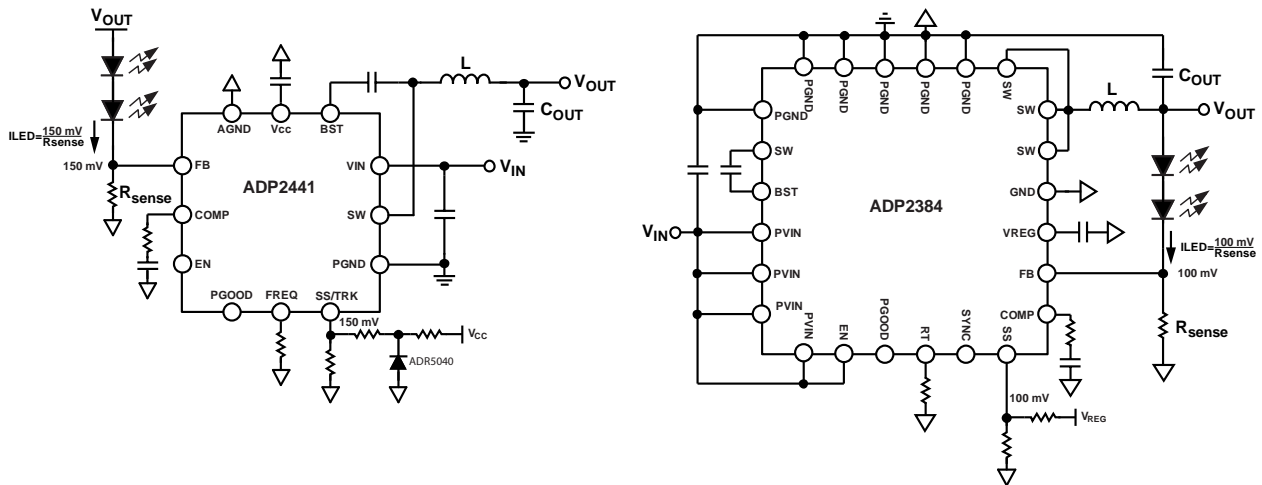

Figure 7. Using the SS/TRK Pin to Reduce the FB Reference Voltage

Using an SS or TRK pin accommodates many, but not all, buck regulators. Some ICs do not have an SS or TRK pin. Also, the SS pin of some buck ICs changes the peak inductor current—not the FB reference, so review the data sheet carefully. If either of these situations is the case, then a

different trick can be used: offset the R_{SENSE} voltage. A resistor divider tied to an accurate rail between FB and R_{SENSE} provides a fairly constant offset voltage between R_{SENSE} and the FB pin.
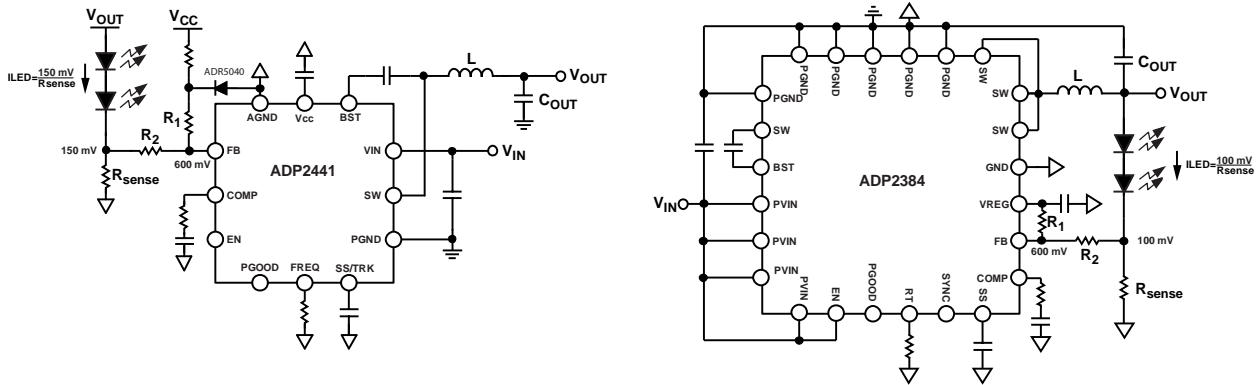

Figure 8. Offset the R_{SENSE} Voltage

The necessary values for the resistor divider can be found in the following equation:

$$R1 = R2 \times \frac{V_{SUP} - FB_{REF}}{FB_{REF} - FB_{REF(NEW)}}$$

So to get an effective feedback reference of 150 mV, with R2 = 1 kΩ and V_{SUP} = 5 V:

$$R1 = 1\ k\Omega \times \frac{5.0V - 0.6V}{0.6V - 0.15V} = 9.78\ k\Omega$$

Now, the LED current is equal to:

$$ILED = \frac{FB_{REF(NEW)}}{R_{SENSE}}$$

Using this method does not require an SS or TRK pin. Additionally, the FB pin will still regulate to 600 mV (but the voltage at R_{SENSE} regulates to the $FB_{REF\,(NEW)}$ voltage). This means that other functions of the chip (like soft start, tracking, and power good) will still function normally.

The downside is that the offset between R_{SENSE} and FB is strongly influenced by the accuracy of the supply. A precision reference like the ADR5040 has little problem, but if the reference was a ±5% reference, it would create a ±12% variation in the LED current. A comparison is shown in Table 1.

Table 1.

Option 1: Use SS/TRK to Reduce FB Reference	Option 2: Offset R_{SENSE} Voltage
±5% supply voltage variation gives ±5% error on ILED. This is not impacted by the V_{SENSE} voltage; therefore, this method has the best R_{SENSE} power dissipation.	±5% supply voltage variation gives ±12% error on ILED. Higher V_{SENSE} voltages improve this.
Very good open/short LED protection. FB_OVP does not factor into intermittent open protection. LED current is limited by the inductor and the control loop speed.	Very good open/short LED protection. Additionally, some ICs have another FB reference (FB_OVP) that immediately disables switching if FB rises 50 mV to 100 mV above normal. This gives a guarantee for the maximum LED overcurrent during intermittent faults.
PGOOD will always remain low.	Since FB pin still regulates to 600 mV, the PGOOD pin functions normally.
By keeping the SS/TRK pin lower than normal, some fault modes may not work properly.	All fault modes work normally.

The other key for accurate current regulation is proper layout routing to the sense resistor. Sensing the resistor at the wrong point can result in several millvolts of error at the FB pin, which will degrade the LED accuracy significantly. A 4-terminal sense resistor is ideal but more expensive. However, by following good layout techniques, high accuracy can also be obtained from a traditional 2-terminal resistor. Marcus O'Sullivan has published an excellent paper on the subject at

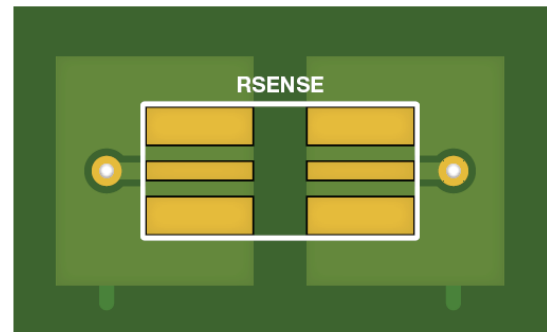http://www.analog.com/library/analogDialogue/archives/46-06/shunt_resistors.pdf

Figure 9. Recommended PCB Trace Routing for R_{SENSE}[4]

Regulating the LED current is easy. The real challenge comes in trying to duplicate all the smart features that a dedicated LED buck regulator gives. Some of the more popular ones are LED short/open fault protection, R_{SENSE} open/short fault protection, PWM dimming, analog dimming, and current foldback thermal protection.

A standard buck converter usually has no problem dealing with shorted or open LEDs. A shorted LED appears like a lower voltage load, and the buck IC adjusts its duty cycle to compensate. An open LED looks like an open load to the buck IC, so it delivers maximum duty cycle, and V_{OUT} rises to its maximum (but no higher than V_{IN})—but no power is delivered. Either of these conditions keeps everything in the system safe. The issue comes with intermittently shorted or open LEDs that occur after startup, and the problem is the output capacitor. The stored energy in the output capacitor creates a huge surge of current through the LEDs when an LED is shorted or an open LED reconnects.

Consider the case of a sudden short across an LED string. The buck regulator controls the duty cycle to give a constant FB voltage, which produces a constant current through the LEDs. This current produces a certain forward voltage (VF) across the LED string, so the buck output capacitor charges to V_{OUT} = VF + VFB. If the VF suddenly drops because an LED in the string is shorted, then the output capacitor sources current to the LED string. This current is equal to I_C = C × ΔVf/Δt (Δt is small and C is often large to minimize L in the

buck LC filter, meaning I_C can become large). An example is shown in Figure 10.
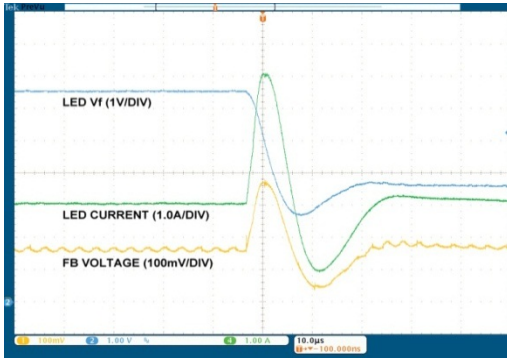

Figure 10. Response to a Shorted LED with C_{OUT} = 10 μF and L = 47 μH

A similar issue arises for an intermittently open string: V_{OUT} charges to its maximum value. Then, when the LED reconnects, a huge inrush of current shoots through the LEDs. However, if that output capacitor wasn't there, then there would be no problem. Dare we remove one of the four key elements of a buck? Fortunately, LEDs do not care if they have some ripple on them, and our feedback loop will ensure that the average LED current remains the same. Therefore, by removing the capacitor, we solve some potential problems and save ourselves one of the larger parts on the bill of materials (BOM). Now, our LED current is exactly equal to our inductor current, and the ripple on the inductor current is reflected in the FB voltage.
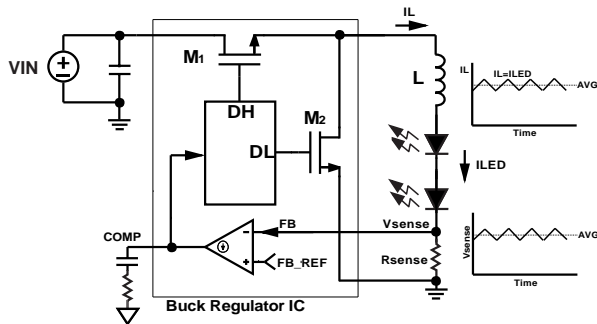

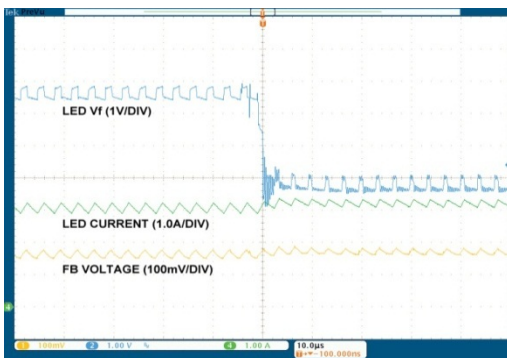*Figure 11. Buck LED Driver Operation without C_{OUT}*

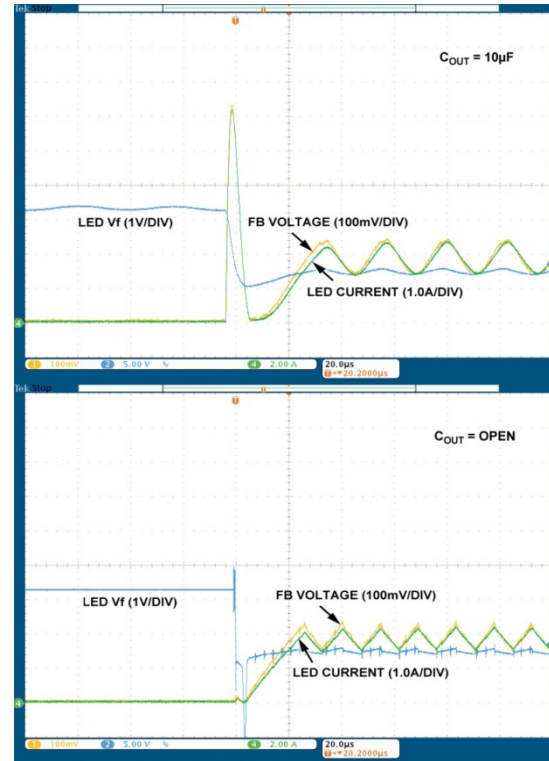*Figure 12. Response to Intermittently Shorted LED with C_{OUT} = 10 μF and C_{OUT} = Open*

Figure 13. Response to Intermittently Open LED with C_{OUT} = 10 μF and C_{OUT} = Open

Eliminating C_{OUT} has another benefit: since ILED = IL, and IL is well controlled (since buck ICs go through great effort to limit the maximum inductor current), we now have another level of LED safety. The LED current will never rise above the buck's peak current limit value: for the ADP2441, this is 1.7 A (typ) and for the ADP2384, it is 6.1 A (typ). This is useful for another fault case: an intermittently shorted R_{SENSE}.

Shorting R_{SENSE}, or shorting the FB pin to GND, can be catastrophic: duty cycle rises to maximum value, which delivers maximum power, and you essentially have V_{IN} applied directly to the LEDs. This gives an uncontrolled and very high current through the LEDs. Most bucks will limit this maximum current, their peak inductor current level, or enter a hiccup protection mode, but by eliminating the output capacitor, we also protect the LEDs against R_{SENSE} shorts that occur after startup.

Therefore, our slightly modified synchronous buck topology helps quite a bit with common LED fault cases. However, as with anything, there are trade-offs; the trade-off here is ripple current through the LED. This ripple current is at a very high frequency (the switching frequency—generally >300 kHz), so visible flickering and acoustic noise is not an issue. The only real issue is to ensure that the LEDs do not exceed their maximum current rating. This is somewhat vague on most LED data sheets. Many LED data sheets will

specify a surge current rating and a dc current rating, but the area of a high frequency ripple on top of a dc value isn't usually covered. The safest approach is to make the peak of the LED ripple below the dc rating of the LED. This means picking a higher value inductance to keep the ripple small. These inductors are either physically larger or will have a higher resistance (DCR). Alternatively, we can leave the inductor the same and choose a higher switching frequency to keep the current ripple low. However, this increases the switching power losses. So, if the maximum rated LED current is close to the maximum average desired out current, then there may be some trade-offs between board area, cost, or power loss.

Another key requirement for a smart LED driver is dimming controls. There are two types of LED dimming: PWM and analog. PWM dimming pulses the LED current. If the frequency is above ~120 Hz, then the human eye averages these pulses to produce a perceived average luminosity. Analog dimming scales the LED current and the current is always constant (dc).

To achieve PWM dimming, we could insert an NMOS in series with R_{SENSE} and open and close it. That would definitely pulse the output current, but at these current levels, we would need to use a power NMOS. Adding one of those defeats the solution size and cost benefits of having the power switches internal to the buck regulator. Instead, it is easier to PWM dim by quickly shutting the buck on and off.

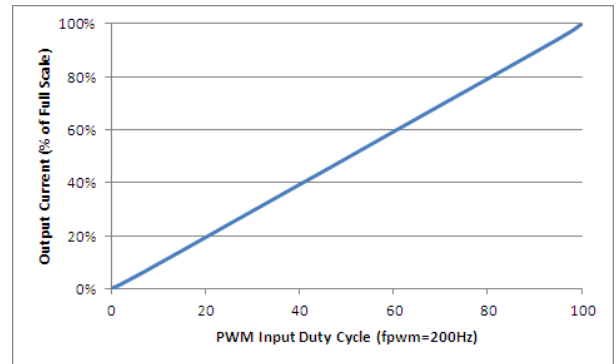For low PWM frequencies (<1 kHz) this can still give great accuracy (Figure 14).

Figure 14. ADP2384 PWM Dimming Linearity

The ADP2384, like all general-purpose bucks, doesn't have a pin to apply a PWM dimming signal, but we can manipulate the FB pin to enable and disable switching. If we pull FB high, then the error amplifier goes low, and the buck switching stops. If we connect FB to R_{SENSE}, then it resumes normal regulation. We can do this with either a small signal (low current) NMOS, or just a general-purpose diode. In the case of an NMOS a high PWM signal shorts R_{SENSE} to FB, enabling LED regulation. A low PWM signal turns the NMOS off, and a pull-up resistor brings FB high. In the case of the diode, a high PWM signal produces no LED current, which is a little backwards from the typical convention. Both solutions are illustrated in Figure 15.
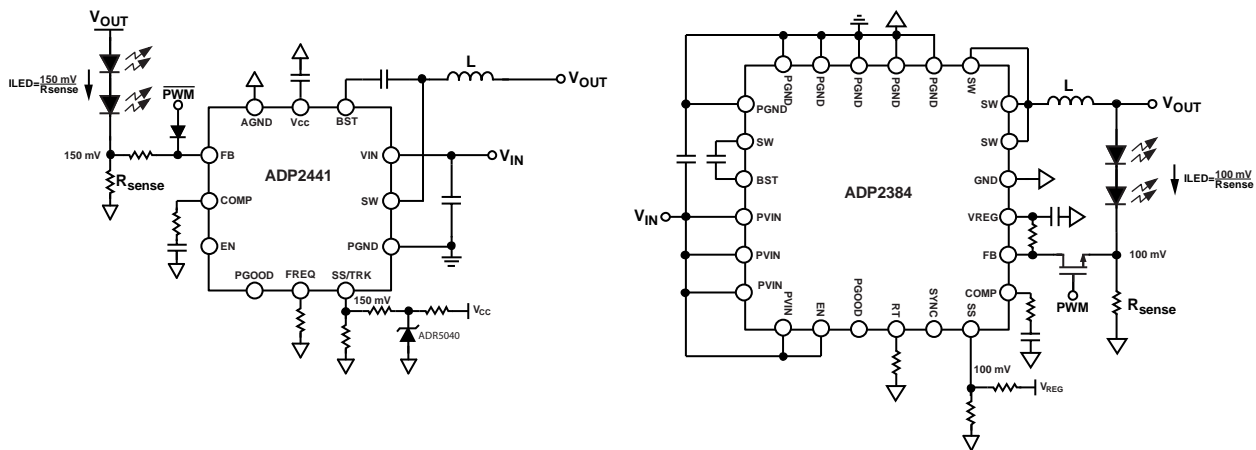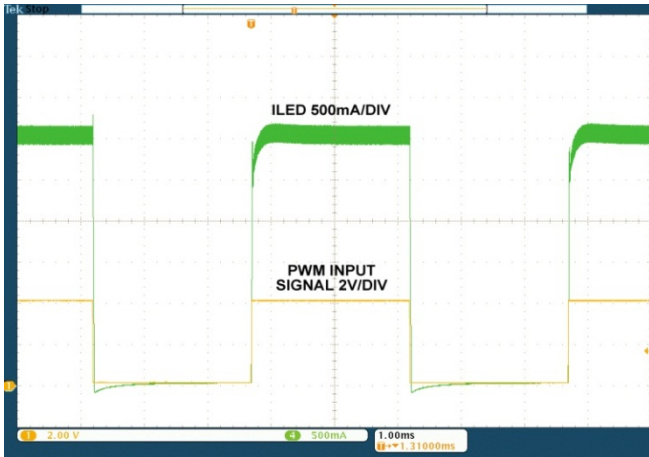

Figure 15. PWM Dimming Options

Figure 16. PWM Dimming Waveform

PWM dimming is very popular, but sometimes noiseless analog dimming is required. Analog dimming scales the LED current, whereas PWM dimming chops it up. Analog dimming is also required if two dimming inputs are used. PWM dimming on top of another PWM dimming signal can create beat frequencies, which could result in light flicker or audible noise. So, we might PWM for one dimming control and analog dim for another dimming control. On a general-purpose buck regulator, the easiest way to implement analog dimming is to manipulate the FB reference that we constructed earlier. This is accomplished by making the analog dimming control voltage the supply for our FB reference adjustment circuits.
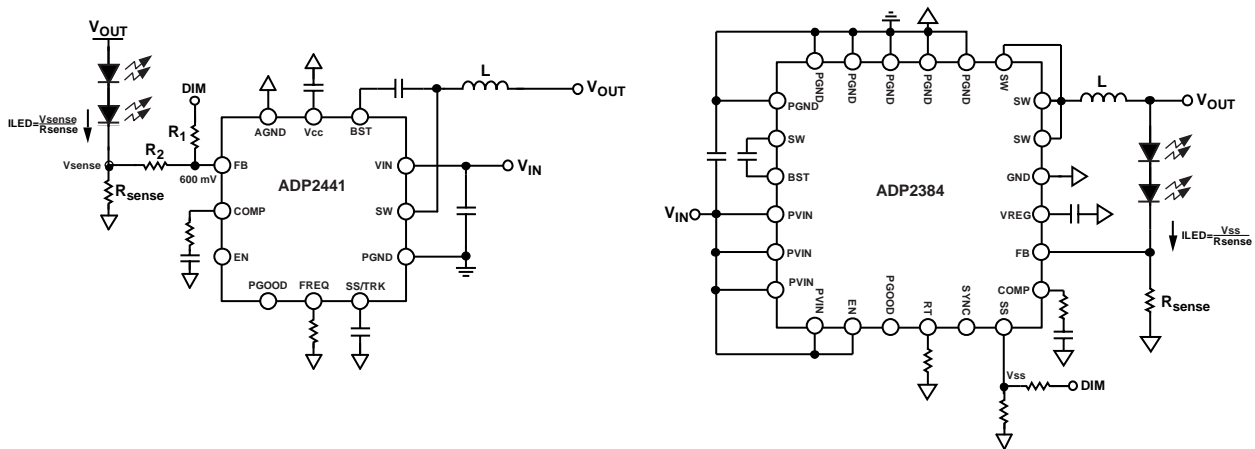

Figure 17. Analog Dimming Circuits

Since the lifetime of the LEDs is heavily dependent on their operating junction temperature, it is sometimes necessary to monitor the LED temperature and respond if the temperature is too high. An abnormally high temperature could be caused by a poorly connected heat sink, an unusually hot ambient, or some other extreme condition. A common solution is to reduce the LED current if the temperature exceeds some threshold. This method is called LED thermal foldback.
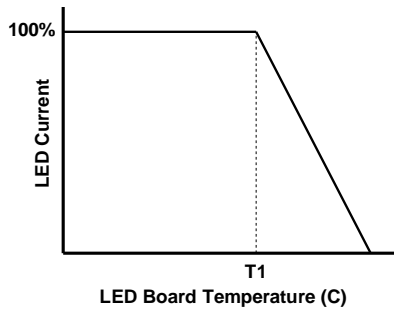

Figure 18. Desired LED Thermal Foldback Curve

In this type of dimming, we wish to keep the LEDs at full current until some temperature threshold (labeled T1 in Figure 18) is reached. At that threshold, we start to decrease the LED current with increasing temperature. This limits the junction temperature of the LEDs and preserves their lifetime. A low cost NTC (negative temperature coefficient) resistor is commonly used to measure the LED heat sink, and a small modification to our analog dimming scheme can easily make use of this NTC. If we are using the SS/TRK pin to control the FB reference, then a simple method is to place the NTC in parallel with the reference voltage (Figure 19).
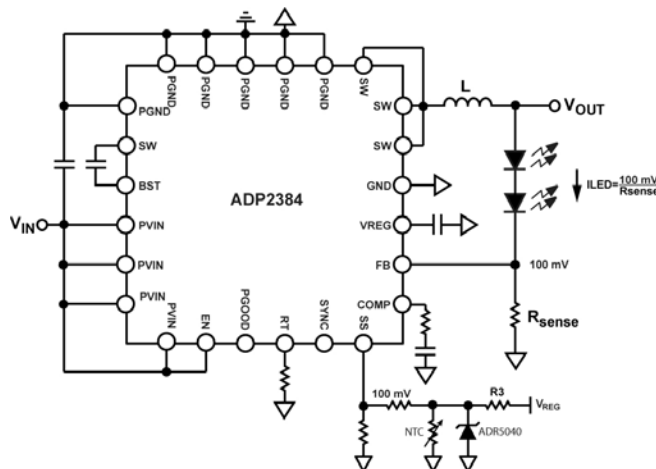

Figure 19. LED Thermal Foldback Using the SS/TRK Pin

The NTC forms a resistor divider with R3. As the heat sink temperature rises, the NTC resistance drops. If the NTC resistor divider's voltage is above the reference voltage, then maximum current is delivered. If the NTC resistor voltage

drops below the reference voltage, then the FB reference voltage, and hence, the LED current drops.

We can also implement the desired temperature dimming profile with the R_{SENSE} offset method. For this method, we just construct a resistor divider with the NTC. This resistor divider attaches to the FB pin with a small signal diode. The diode prevents the resistor divider from acting on the FB pin until the divider reaches about 600 mV + VF. There is some degradation in dimming accuracy, but the results are fairly good (Figure 20).
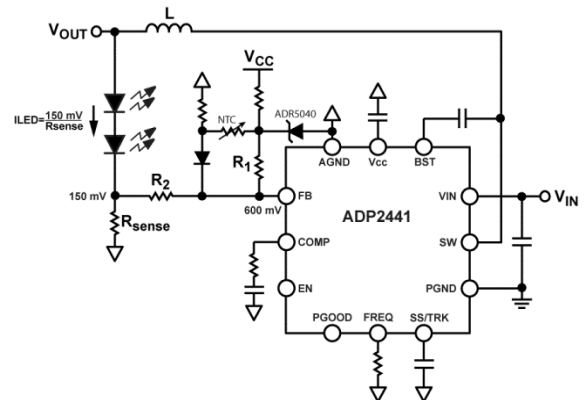

Figure 20. LED Thermal Foldback Using R_{SENSE} Offset Technique

These tips should be taken as general guidelines for implementing comprehensive LED features into a standard buck regulator. Since these features are a little outside of the intended application for the buck IC, it is always best to contact the semiconductor manufacturer and ensure that the IC can handle these modes of operation. For more information on the ADP2441 and ADP2384, or for demo boards of these LED driver solutions, visit http://www.analog.com/lighting.

REFERENCES

[1] DOE SSL 2011 Manufacturing Roadmap (ssl.energy.gov).

[2] David Cox, Don Hirsh, and Michael McClintic. "Are you using all of the lumens that you paid for?" *LEDs Magazine*, Feb. 2012.

[3] Ken Marasco. "How to Apply DC-to-DC Step-Down (Buck) Regulators Successfully." *Analog Dialogue*, Vol. 45, June 2011.

[4] Marcus O'Sullivan. "Optimize High-Current Sensing Accuracy by Improving Pad Layout of Low-Value Shunt Resistors." *Analog Dialogue*, Vol. 46, June 2012.

RESOURCES

Share this article on   facebook   twitter