EXPONENTIAL GROWTH of LED lighting has ushered in a vast selection of integrated circuit devices to provide controlled power to LEDs. No longer acceptable to an energy-conscious world, switch-mode LED drivers have long since replaced power hungry linear current sources as the standard. Applications ranging from flashlights to streetlights to stadium scoreboards all require precise control of LED light output, commonly referred to as luminous flux.

Luminous flux (lumens) is a measure of the useful power emitted by a light source. This metric is a weighted function of the power at each wavelength and is tailored to match the human eye’s response across the visible spectrum. Luminous flux emitted by an LED is directly proportional to the drive current. In many instances, real-time changes in light output, and consequently LED drive current, are required. This function is commonly referred to as dimming control.

Controlling color can also be paramount in many dimming applications. High brightness white LEDs are typically implemented with a blue LED emitter covered by a phosphor coated dome. Color temperature is a metric that describes the color of the light compared to a known reference (the blackbody curve). LED manufacturers specify the nominal color temperature of a white LED; however, it varies significantly with forward current, junction temperature, and lifetime. Most colored LEDs, which have no phosphor, only specify dominant wavelength instead of color temperature, but are also subject to shifts in wavelength.
BACKGROUND

Fig. 1 shows a switch-mode LED driver in a buck topology where the input voltage $V_{IN}$ is higher than the output voltage $V_{OUT}$ (across the LEDs + $R_{SNS}$). Energy is processed and transferred from input to output by the controlled switch (internal to the LM3406 shown in Fig. 1.) diode D1 and inductor L1. The energy transfer occurs at the switching frequency which is usually somewhere between 50 KHz and 1 MHz, depending upon the application. The LED current is regulated by monitoring the average voltage across the sensor resistor $R_{SNS}$ at the CS pin. The duty cycle driving the internal switch is dynamically changed, increasing or decreasing the LED current to maintain regulation at the CS pin.

There are two popular methods for dimming LEDs in switch-mode driver circuits:

- **Pulse Width Modulation (PWM) dimming**
- **Analog dimming**

Both methods control the time-averaged current through the LEDs, but there are differences between the two which become evident when examining the advantages and disadvantages of the two types of dimming circuits. Besides the functional differences which are discussed in the following sections, Table 1 compares advantages and disadvantages of each method.

Analog dimming using any switch-mode driver is accomplished by the adjustment of the nominal LED current. Theoretically, analog dimming with the LM3406 shown in Fig. 1 could be accomplished by an adjustment of $R_{SNS}$. However, in practice, the $R_{SNS}$ value is very small (sub 1 Ω) to limit the power dissipation in the sensor. There are no standard potentiometers that provide a variable resistance this small. Instead, a more complex technique can be used to directly control the nominal LED current using a fixed sense resistor. The op-amp shown in Fig. 1 can be placed between the CS pin and $R_{SNS}$ to buffer and amplify the sensed voltage. A much higher resistance potentiometer is placed in the feedback path from input to output of the op-amp to adjust the effective sense voltage, thereby analog dimming the LEDs.

The main disadvantage of analog dimming is a relatively large color temperature/wavelength shift with respect to average LED current. Depending on the application, this may or may not be critical. For instance, in a standard low-cost flashlight using phosphor coated white LEDs, color temperature shift can go relatively unnoticed. By comparison, a backlight display using RGB (red, green, and blue) LEDs cannot tolerate the wavelength shift associated with analog dimming. The relatively simplicity and cost of analog dimming makes it an attractive solution for some applications, but not all. In situations where the color of the LEDs is critical, or the particular LED exhibits a large change in color temperature with changes in LED current, dimming the output of the LED by changing the LED current would be prohibitive.

**PWM DIMMING**

In contrast to analog dimming, PWM dimming is implemented, not by adjusting the nominal LED current, but by turning on and off the switching controller at a much lower frequency than the switching frequency. This creates...
A modulated output signal whose average is equal to the fixed nominal LED current, multiplied by the duty cycle of the PWM drive signal. The PWM frequency can range from hundreds of Hz to tens of kHz, but must be faster than the human eye can detect, to avoid a perceived flickering effect; this is commonly restricted to frequencies greater than or equal to 200 Hz.

With PWM dimming, the LED current is either zero or at the nominal LED current level. This greatly improves the color shift phenomena associated with analog dimming and is the preferred choice for applications needing precise color control. One disadvantage is the added switching noise associated with the PWM action of the LED current. Of course, the need to generate a PWM input signal adds to cost and complexity as well.

Many LED drivers feature a specialized PWM DIM pin (Fig. 3a) that accepts a wide range of PWM frequencies and amplitudes allowing a simple interface to external logic. The DIM function shuts-down the internal switch, disabling the output to the LED driver, while leaving the internal bias circuitry operating, avoiding the delay of restarting the IC. The minimization of delays allows for greater dimming range. The minimum achievable duty cycle in this type of PWM dimming implementation is limited by the rise and fall time (slew rate) of the inductor (Fig. 3b). PWM dimming via the DIM pin is used for many applications from automotive headlights to general downlighting.

For more complicated applications like television backlighting, there is a need for extremely large dimming ranges. This is only possible using parallel FET dimming (Fig. 3a). The switch is turned off and on to redirect the LED current through the switch and back through the LEDs at the desired duty cycle. The rise and fall times of the LED current are an order of magnitude quicker, because they do not depend on the inductor’s slew rate. Fig. 3b shows how this allows for a much smaller minimum achievable duty cycle, which greatly improves dimming range.

**TWO-WIRE PWM DIMMING**

Two-Wire PWM dimming is a popular method for automotive interior lighting. These applications were originally used with incandescent loads. The interior light power...
source was directly modulated to reduce the average voltage across the resistive load, thereby dimming the lights. As the automotive world transitioned to LEDs, the existing infrastructure was still desirable to some manufacturers. This presented a problem to switch-mode power supplies where the output is being regulated, regardless of the state of the input. To use this dimming information embedded in the power source, a means to decode the dimming angle was necessary.

Fig. 2 shows one approach to implementing two-wire dimming with a switch-mode LED driver. As V_{IN} rises and falls, the V_{INS} pin detects the duty cycle and converts the PWM waveform into a corresponding PWM of the output drive. The disadvantage to this method is that a large input capacitance C_{IN} is necessary to provide the input power when the source is turned off each cycle. In addition, a high voltage diode D_{1} is necessary to ensure the V_{INS} pin can detect the modulated signal.

DIMMING AND EFFICIENCY
LED luminous efficacy is loosely defined as the visible output power in lumens, divided by the input electrical power in watts (lumens/W). Any electrical power that goes into the LED that does not result in visible light has been converted to heat or non-visible electromagnetic radiation. It is a known fact that all LEDs are more efficient when driven with less forward current. The typical relationship between forward LED current and luminous flux is shown in Fig. 5. As the slope of the characteristic deviates from the ideal line, the efficacy is decreasing.

From Fig. 5, one can see that LED efficacy is greater with analog dimming relative to PWM dimming at lower DIM levels. Consider a PWM dimmed LED with a low duty cycle; the LED peak current is much higher than the time-averaged LED current. On the other hand, an analog-dimmed LED only operates at the average current level.

TABLE 1. ADVANTAGES AND DISADVANTAGES OF ANALOG AND PWM DIMMING

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ANALOG DIMMING</th>
<th>PWM DIMMING</th>
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<tbody>
<tr>
<td>Ease of Design</td>
<td>Easier if controller fitted with analog dim pin.</td>
<td>Requires processor or timers to create PWM input signal.</td>
</tr>
<tr>
<td>Relative Cost</td>
<td>Usually cheaper to derive analog input signal.</td>
<td>More expensive to implement PWM input signal.</td>
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<tr>
<td>Shift in Color</td>
<td>Dimming produces visible color shift.</td>
<td>Relatively constant color over all dim levels.</td>
</tr>
<tr>
<td>Temperature</td>
<td>Fairly limited in most designs.</td>
<td>Can achieve very high contrast ratios.</td>
</tr>
<tr>
<td>Dimming range</td>
<td>Changes to dim range hardware adjustable</td>
<td>Changes to dim range possibly software adjustable</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Better than PWM at lower dim levels</td>
<td>Lower efficacy at high peak currents</td>
</tr>
<tr>
<td>Efficacy</td>
<td>No low frequency envelopes of current pulses</td>
<td>PWM presents a low-frequency current draw to the system. This may couple into other circuitry.</td>
</tr>
<tr>
<td>Interaction Issues</td>
<td>Usual issues with switching supplies</td>
<td>LED shunt FET could exhibit hard edges that can be radiated or conducted.</td>
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COMBINING DIMMING FUNCTIONS
National Semiconductor’s LM3409 is a unique LED driver in that it provides functionality for easy analog and PWM dimming. Analog and PWM dimming can be performed separately or concurrently, allowing for a wide range of very simple to very complex dimming schemes. Fig. 4 shows a typical analog dimming application using the LM3409 LED driver.

There are four possible
ways to implement LED dimming using the LM3409:
1. Analog dim by directly driving the $I_{\text{ADJ}}$ pin with a voltage source from 0V to 1.24V
2. Analog dim by placing a potentiometer between $I_{\text{ADJ}}$ pin and Gnd.
3. PWM dim with the Enable pin
4. PWM dim by external shunt FETs.

The LM3409 is a hysteric part. The main switch Q1 is turned on and energy begins to transfer from input to output. When the switch reaches the peak threshold, Q1 is turned off. Then, a constant, off-timer, proportional to the output voltage, determines the off time. Analog dimming is performed by varying the internal peak current sense threshold from 0 to 248 mV. If the $I_{\text{ADJ}}$ pin is left open, the internal 5 µA current source biases the pin to 1.24 V, giving the maximum LED current threshold at 248 mV across the sense resistor $R_{\text{SNS}}$.

If a potentiometer is placed from $I_{\text{ADJ}}$ to Gnd, the 5 µA current source biases $R_{\text{ADJ}}$ to create a voltage that varies the internal current sense threshold. In the same manner, the $I_{\text{ADJ}}$ pin can be driven directly with a DC voltage from 0 to 1.24 V to scale the current threshold from 0 to 248 mV.

Fig. 6 is a plot of measured LED current vs. the potentiometer resistance between the $I_{\text{ADJ}}$ pin to Gnd. The transfer function of LED current to potentiometer resistance is basically linear, except at very low dimming. The maximum current is limited to 1 A because of the internal 2.5 V clamp shown in Fig. 4.

PWM dimming of the LM3409 is identical to the LM3406, except instead of a dedicated DIM pin, the EN pin is used. The EN pin is a logic input that uses the PWM input signal to turn on and off the main FET Q1. The only difference between the LM3409 and the LM3406 is that if the EN pin is pulled low long enough the LM3409 completely turns off. Parallel shunt FET dimming can be implemented with the LM3409 as well.

The advantages and disadvantages shown in Table 1 highlights the benefits of a combined dimming approach using the LM3409 LED driver. As the LED lighting industry advances, combined dimming methods are sure to become more popular with designers seeking to improve dimming performance, while maximizing efficiency and minimizing color shift.