

AN-1656 Design Challenges of Switching LED Drivers

ABSTRACT

Using a switching regulator as an LED driver requires the designer to convert a voltage regulator into a current regulator. Beyond the challenge of changing the feedback system to control current, the LEDs themselves present a load characteristic that is much different than the digital devices and other loads that require constant voltage. The LED WEBENCH® online design environment predicts and simulates the response of an LED to constant current while taking into account several potential design parameters that are new to designers of traditional switching regulators.

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1 Output Voltage Changes when LED Current Changes

In the first step of the LED WEBENCH tool, "Choose Your LEDs", an LED is selected with a standard forward current, I_F . This default value is provided by the LED manufacturers, and in most cases it represents the testing condition for that LED. Typical values for high-power LEDs are 350 mA, 700 mA, and 1000 mA.

Not all designs will use a standard current, however. The designer can select a different LED current, and then the forward voltage will change in the V_{LED} box under step 2. The change in voltage comes from LEDs' V-I curve. [Figure 1](#) shows a curve from a 5W white (InGaN) LED that differs from the curves normally found in LED datasheets. LED manufacturers provide these curves, but they are often shown as I-V curves with voltage as the independent quantity. In [Figure 1](#), forward current is the independent variable, reflecting the fact that in LED drivers current is controlled, and voltage is allowed to vary. The cross-hairs intersect at the standard/typical I_F and V_F values of 350 mA and 3.5V, respectively.

Once the V_F of the LEDs has been determined from the V-I curve, the LED driver's output voltage is calculated using the following formula:

$$V_O = n \times V_F + V_{SNS}$$

where

- n is the number of LEDs connected in series
- V_{SNS} is the voltage drop across the current sense resistor

(1)

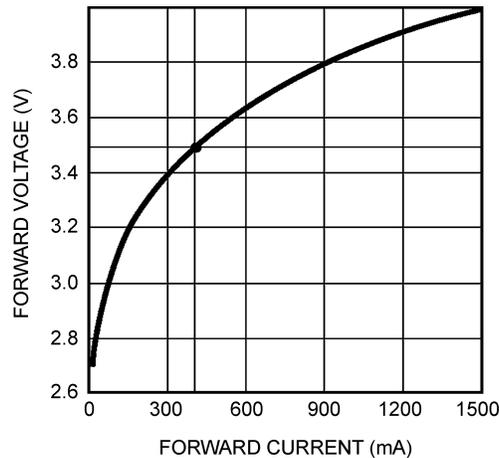


Figure 1. V-I Curve with Typical V_F and I_F

2 Designing for V_{O-MIN} and V_{O-MAX}

In practice, the typical value of V_F changes with forward current. Further analysis of total output voltage is needed because V_F also changes with process and with the LED die temperature. The more LEDs in series, the larger the potential difference between V_{O-MIN} , V_{O-TYP} and V_{O-MAX} . An LED driver must therefore be able to vary output voltage over a wide range to maintain a constant current. I_F is the controlled parameter, but minimum and maximum output voltage must be predicted in order to select the proper regulator topology, IC, and passive components.

A typical example that can lead to trouble is driving three white (InGaN) LEDs from an input voltage of $12V \pm 5\%$. In Figure 2, each LED operates at the typical V_F of 3.5V, and the current sense adds 0.2V for a V_O of 10.7V. Minimum input voltage is 95% of 12V, or 11.4V, meaning that a buck regulator capable of high duty cycle could be used to drive the LEDs.

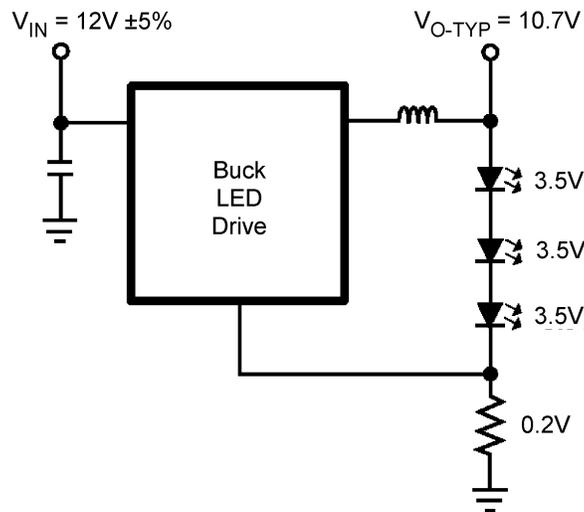


Figure 2. $V_{IN-MIN} > V_{O-TYP}$, Buck Regulator Works

However, a buck regulator designed for the typical V_O will be unable to control I_F if V_{O-MAX} exceeds the minimum input voltage. The same white LEDs with a typical V_F of 3.5V have a V_{F-MAX} of 4.0V. Headroom is tight under typical conditions, and the buck regulator will lose regulation with only a small increase in V_F from one or more of the LEDs (Figure 3).

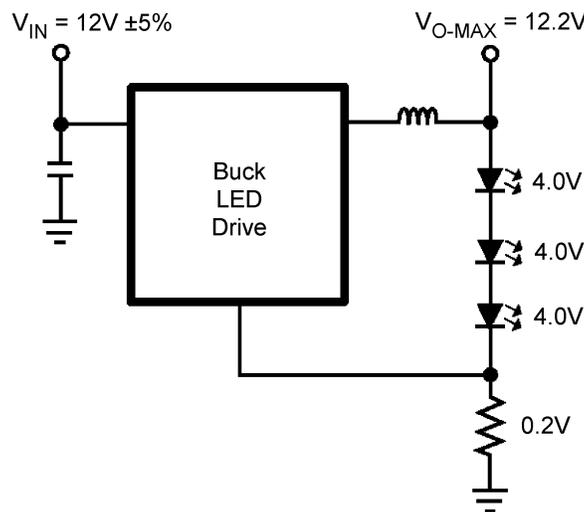


Figure 3. $V_{IN-MIN} < V_{O-MAX}$, Buck Regulator Fails to Regulate

3 Pitfalls of Parallel LED Arrays

Whenever LEDs are placed in parallel, the potential exists for a mismatch in the current that flows through the different branches. The forward voltage, V_F , of each LED varies with process, so unless each LED is binned or selected to match V_F , the LED or LED string with the lowest total forward voltage will draw the most current (Figure 4). This problem is compounded by the negative temperature coefficient of LEDs (and all PN junction diodes). The LEDs that draw the most current suffer the greatest increase in die temperature. As their die temperature increases, their V_F decreases, creating a positive feedback loop. Elevated die temperature both reduces the light output and decreases the lifetime of the LEDs.

The system in Figure 4 also illustrates a potential over-current condition if one of the LEDs fails as an open circuit. Without some protection scheme, the entire drive current I_O will flow through the remaining LED(s), likely causing thermal overstress. Likewise, if one of the LEDs fails as a short circuit, the total forward voltage of that string will drop significantly, causing higher current to flow through the affected branch.

To maintain safety and reliability in a parallel LED system, forward voltage should be binned or matched. Fault monitoring should detect LEDs that fail as either short or open circuits. Finally, the entire array should have evenly distributed heat sinking, to ensure that V_F change with respect to die temperature occurs uniformly over all the LEDs.

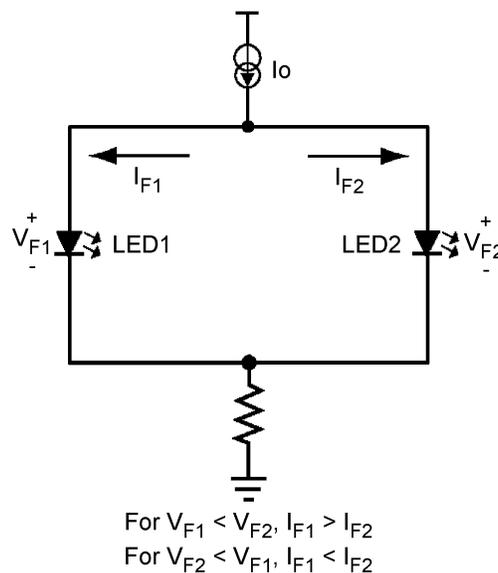


Figure 4. Mismatched LEDs in Parallel

4 Selecting LED Ripple Current

LED ripple current, Δi_F , in an LED driver is the equivalent of output voltage ripple, Δv_O , in a voltage regulator. In general, the requirements for Δi_F are not as tight as output voltage ripple. Where a ripple of a few millivolts to 4%_{p-p} of V_O is typical for Δv_O , ripple currents for LED drivers range from 10% to 40%_{p-p} of the average forward current, I_F . Figure 5 and Figure 6 show a typical ripple current of 25%_{p-p} from a buck switching LED driver. A wider tolerance for Δi_F is acceptable because the ripple is too high in frequency for the human eye to see. General illumination applications (Such as lamps, flashlights, signs, and so on) can tolerate large ripple currents without harming the quality or character of the light. Allowing larger ripple current means lower inductance and capacitance for the output filter, which in turn translates to smaller PCB footprints and lower BOM costs. For this reason, Δi_F should generally be made as large as the application permits.

The true upper limit for Δi_F comes from the nonlinear proportion of heat to light that is generated as the peak current through the LED increases. Above approximately 40%_{p-p} ripple, the LED can experience more heating during the peaks than cooling during the valleys, resulting in higher die temperature and reduction in LED lifetime.

Some high-end applications require tighter control over LED ripple current. These include industrial inspection, machine vision, and blending of red, green, and blue for backlighting or video projection. The higher system cost of these applications justifies larger, more expensive filtering to achieve ripple currents in the sub 10%_{p-p} region.

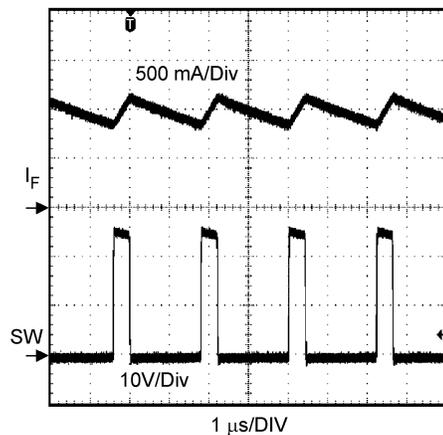


Figure 5. LED Current (DC and AC)

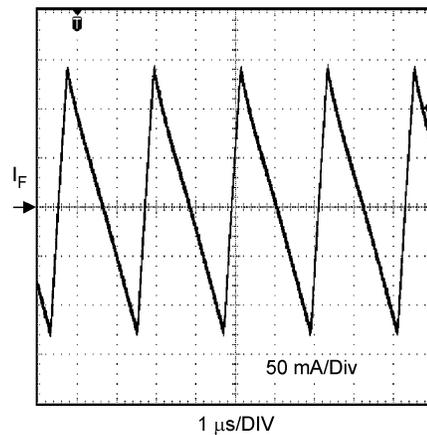


Figure 6. Only LED Ripple Current

5 Dynamic Resistance

Load resistance is an important parameter in power supply design, particularly for the control loop. In LED drivers it is also used to select the output capacitance needed to achieve the desired LED ripple current. In a standard power supply that regulates output voltage, the load resistance has a simple calculation:

$$R_o = V_o / I_o \tag{2}$$

When the load is an LED or string of LEDs, however, the load resistance is replaced with the dynamic resistance, r_D and the current sense resistor. LEDs are PN junction diodes, and their dynamic resistance shifts as their forward current changes. Dividing V_F by I_F leads to incorrect results that are 5 to 10 times higher than the true r_D value.

Typical dynamic resistance at a specified forward current is provided by some manufacturers, but in most cases it must be calculated using I-V curves. (All LED manufacturers will provide at least one I-V curve.) To determine r_D at a certain forward current, draw a line tangent to the I-V slope as shown in [Figure 7](#). Extend the line to the edges of the plot and record the change in forward voltage and forward current. Dividing ΔV_F by ΔI_F provides the r_D value at that point. [Figure 8](#) shows a plot of several r_D values plotted against forward current to demonstrate how much r_D shifts as the forward current changes.

One amp is a typical driving current for 3W LEDs, and the following calculation shows how the dynamic resistance of a 3W white InGaN was determined at 1A:

$$\Delta V_F = 3.85V - 3.48V$$

$$\Delta I_F = 1.5A - 0A$$

$$r_D = \Delta V_F / \Delta I_F = 0.37 / 1.5 = 0.25\Omega$$

Dynamic resistances combine in series and parallel like linear resistors, hence for a string of 'n' series-connected LEDs the total dynamic resistance would be:

$$r_{D-TOTAL} = n \times r_D + R_{SNS} \tag{3}$$

A curve-tracer capable of the 1A+ currents used by high power LEDs can be used to draw the I-V characteristic of an LED. If the curve tracer is capable of high current and high voltage, it can also be used to draw the complete I-V curve of the entire LED array. Total r_D can be determined using the tangent-line method from that plot. In the absence of a high-power curve tracer, a laboratory bench-top power supply can be substituted by driving the LED or LED array at several forward currents and measuring the resulting forward voltages. A plot is created from the measured points, and again the tangent line method is used to find r_D .

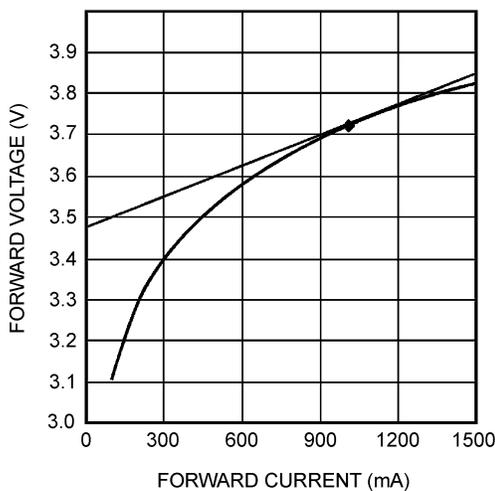


Figure 7. V_F vs I_F

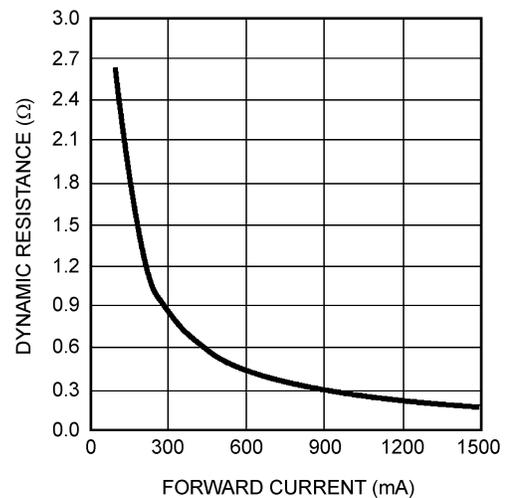


Figure 8. r_D vs I_F

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