Overcome the challenges of driving parallel LED strings

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LEDs are finding their way into more products than ever before. Automotive lighting, TV backlights and tablets are just a few applications that require multiple LEDs. Driving a large number of LEDs with a constant current can be done with either a lengthy series connection or by driving multiple strings in parallel. But connecting many LEDs in a long series string poses high-voltage and single-point failure issues. Similarly, powering multiple strings in parallel requires multiple current regulators, one for each string. Ultimately, this leads to higher complexity and cost. Today's trend is to operate strings in parallel, and this article explores options and the rational for implementing circuitry to achieve this goal.

An LED is similar to a standard diode by virtue of being a current-driven device. It has an I-V curve in which the current and voltage are non-linear and a small change in its forward voltage can translate into a large current change. Since the LED current in nearly proportional to the LED’s luminous flux, it is important in applications such as TVs to control the current accurately. But not all applications necessarily require high accuracy for brightness matching of the LEDs. If the LEDs are driven in a single string, there is inherent matching because each LED has the same current level. As the number of LEDs in use increases, paralleling strings becomes necessary, and a choice must be made as to how to control the current in each string.

A typical white LED can have a forward voltage of 3.3V with as much as a 20% variation at its rated current. If 10 LEDs are used in series, it’s possible that one string may require 33V to adequately drive it, while a second string requires 39.6V at the same current. If these two strings are wired in parallel, the lower voltage string pulls significantly more current than intended and the second significantly less. The probability that all the LEDs in one string would fall at the high end of its forward voltage specification is rather small and this probability decreases as more LEDs are used.

In reality, balancing between these two strings is much better, but there could still be a difference of several volts. To help this situation, LED manufacturers use binning to sort parts into groups that accurately match the LEDs forward voltage (Vf) drops (as well as flux and wavelength) to allow better performance. Figure 1A shows a simple, low-cost implementation for paralleling two strings. A fixed-voltage source and a simple resistor to set the current level is all that is necessary.

The voltage across one sense resistor can be regulated by an external control circuit to adjust the output voltage higher or lower to accurately control the LED current. While this regulates the LED current in one string, it does not necessarily do a good job for the second. It can actually make the current in the second worse, as in the case where the control loop increases the output voltage for the regulated string, but the second string has the lower voltage drop of the two.

As in standard diodes, the forward drop of LEDs decreases with increasing temperature. If one
string gets significantly hotter than the other, its forward drop decreases and it begins to draw more current. This added dissipation heats it further, increasing its current and possibly leading to LED failure due to this thermal runaway. This situation requires that the voltage driving the strings is current regulated and is constant. Additionally, all LEDs should be mounted on a common heatsink to keep the operational temperature between them as equal as possible.

Thermal runaway isn’t a problem when the strings are driven by a constant voltage, but the current matching between strings can be quite poor. Since each string is independent of the other (that is, the current in one is not directly regulating the current in the other), fault tolerance is good when driven by a voltage source, but poor when current is regulated in one string (via Vfb). In this situation, if an LED opens in the regulated string, the voltage driving the strings is commanded higher by the control circuit and eventually causes overvoltage in the unregulated string, leading to failure. While adequate when driven by a voltage source without feedback, the circuit of Figure 1A doesn’t provide accurate current matching in the LED strings for more demanding applications.

Figure 1B implements a current mirror to regulate the currents in both strings. The first string uses voltage feedback (Vfb) from sense resistor Rs1 to regulate its current and relies on Vbe of Q1 and Q2 matching to set the same voltage across Rs2. With the same sense resistor voltage and value, the
same current is forced to flow in the second string. The regulation accuracy largely depends on the matching between the Vbe voltages of Q1 and Q2. For this reason, a dual transistor with both components on the same die helps reduce temperature, processing and lot variations.

This circuit gives reasonable accuracy, but base current mismatch and the Vbe to Rs ratio introduce errors that make it less than perfect. The larger the Vfb voltage is relative to Vbe, the lower the errors will be, but with increasing power dissipation. Adding base resistors in series with Q1/Q2 may also help with accuracy.

**Power Dissipation**

One issue involves the power dissipation in a dual Q1/Q2 part. Most dual transistor *matched pairs* are only available in small packages, such as a SOT-23, which can only tolerate a few hundred milliwatts of power dissipation. If the LEDs in the first string have a larger voltage drop than the second, that voltage difference shows up across the Vce of Q2. This can limit the usable current to less than 100 mA, if a few volts are allocated for LED voltage mismatch.

Another problem is when the first string’s required voltage is less than the second’s. The feedback sets the output voltage to get proper regulation in the first string, but the second doesn’t have enough voltage headroom and the current in that string is reduced. This can be compensated for by adding a series resistor in the first string to add additional voltage to compensate for the second, but this increases losses.

One benefit to the current mirror approach is that it’s expandable to additional strings by simply connecting the bases together. Ultimately, it too is fault intolerant because if an LED in the first string opens, the second string also goes out. But the reverse is not true because the second string tracks the first. So if the second string opens, the first string still operates. Overvoltage protection is required because, if the first string fails open, the output voltage increases without bounds causing the LEDs to overvoltage.
Figure 2. Independent current string regulators provide redundancy.

Figure 2 allows the current in each string to be independently regulated. The output voltage is set to a fixed voltage, with allowance for the maximum possible LED voltage variation. This means that the output voltage is likely to be several volts higher than necessary for at least one string, but the current in each is always regulated to the desired level. The operational amplifier (op amp) controls the FET gate voltage. This varies the FET resistance such that the sense resistor voltage matches the external reference voltage to obtain a regulated LED current. This circuit is similar in operation to a linear regulator. Since the LED current is controlled by local current loops, the output voltage is simply fixed.

This is effective, but less efficient because it burns additional power in the FETs due to the voltage mismatch of the two LED strings. The FETs need to be rated for this power, but an inexpensive FET in a power package is all that is required. The Rds_on can be quite high (generally 1 Ohm or higher is acceptable) and the switching speed slow, because it operates in its linear region. While the complexity of this approach is higher than those shown in Figure 1, it’s more fault tolerant. This approach is capable of handling one or two shorted LEDs and still functioning. If an LED opens, the other string continues to operate unaffected.
Figure 3. Prototype circuit features dynamic headroom adjustment.

Figure 3 is an evaluation circuit that implements Figure 2, but adds additional features. The highlighted level shifter block (D33-D35) addresses the higher power losses associated with Figure 2. It adds a feedback loop to regulate and limit the voltage on the drain of the FETs to 1V. Since there are two FETs, only the FET voltage of the string with the highest voltage is regulated, and the FET in the lower voltage string absorbs the difference. This circuit only realizes significant loss in the FETs when there is an actual voltage imbalance between the strings and minimizes the losses if the strings are in voltage balance, unlike Figure 2, therefore making it more efficient.

This is a more likely scenario than having them out of balance when using lengthy strings. The FET drain voltage increases or decreases to control the current in the string. For example, if the left string LED current is low, the FET turns on more and its drain voltage decreases (to apply more voltage to the string). The drain voltage is sensed by D33 and D35 (the anode of which has the same potential now as the FET drain) and is sent to the voltage feedback circuit of U3D to increase the output voltage until the FET drain voltage obtains 1V.

This sets the output voltage to \( n \times V_f + 1V \) (where \( n \) is the number of LEDs in a string, and \( V_f \) is the forward drop of a single LED). If the other string’s current is low, the level shifter (D34 and D35) takes over control. The additional components in the level-shifter block function to provide a maximum output voltage in the case of an open LED. This voltage level is determined by a reasonable FET power dissipation, set to \( \sim 0.7W \) and is a function of its package and thermal dissipation capability. If an LED opens, its series FET voltage drops to zero. This makes the output go over voltage since the feedback sees 0V and cannot change it.

These additional level-shift components allow the output voltage to rise to approximately \( n \times V_f + 1V + 5V \), which is a safe voltage for the other string to operate. If an LED shorts, the string’s FET...
absorbs the additional voltage and subsequent power dissipation. This circuit can safely handle two shorted LEDs (for red LEDs with Vf = 2.1V) and still maintain regulation. A second level OV zener (D6) is added in case both strings open up.

If a fault signal is desired, monitoring the LED FET voltage for <1V could indicate that a string is open. An additional feature is an additional control loop that regulates the input current to a maximum set point during startup (or brown-out conditions) so as to not overload the input source. While the circuit of Figure 3 implements many features to control parallel strings of LEDs, similar circuitry has been integrated into modern LED controllers, ultimately saving real-estate and cost. Examples of these controller devices are the LM3492, LM3466, and the LP8556.

Summary

Driving parallel strings of LEDs pose additional design challenges over single strings, such as tolerating voltage imbalance, current regulation methods, minimizing power dissipation and fault conditions. The simplest way to drive parallel strings is with a fixed voltage source and a series current-setting resistor. When higher performance and protection features are required, individual string regulation offers the highest level of regulation accuracy and flexibility. The final circuit shown reduces power dissipation by regulating the headroom of the current regulators as well as detailing protection and fault circuitry.