Does adaptive pre-boost control in automotive-lighting applications boost efficiency?

By Michael Helmlinger, *Systems Engineer*
Arun Vemuri, *Sector GM*

Introduction

Light emitting diode (LED)-based lighting is increasingly popular in automotive applications, including high and low beams in headlights, and brake and taillights in rear lights. Strategy Analytics estimates that nearly 20% of new cars will have LED headlights. LED-based lighting applications use an LED driver circuit to drive the LEDs, with the goal to maintain constant current.

Given the complex design requirements, an extensive selection of LED driver circuits now exist.[1, 2] These circuits include both linear and switching LED drivers that address system-level requirements such as high voltage to drive a long LED string, in addition to current accuracy and stability. LED driver circuits also implement features to mitigate electromagnetic interference (EMI), maintain thermal performance, and improve overall efficiency. There are also features that protect LEDs from damage through thermal foldback, dimming, and current-balancing functionality.[3]

One important consideration in solutions for LED driver circuits is the efficiency, as defined by Equation 1.

$$\eta = \frac{\text{Power\_out}}{\text{Power\_in}} \tag{1}$$

A common circuit topology to drive LEDs is a dual-stage circuit, in which the first stage is a voltage boost and the second stage is a constant-current regulator. This article explores whether it's possible to improve overall efficiency by using adaptive pre-boost control in dual-stage LED driver circuits.

Single- and dual-stage LED driver circuits

Two common architectures used to drive the LEDs are the single-stage and dual -stage LED driver circuits. Figure 1 is a block diagram of a single-stage LED driver circuit. In this circuit, the LED driver is directly connected to the automotive battery. Depending on the number of LEDs in the string and the amount of current being driven into the string, the constant-current regulator could be based on a linear driver circuit or a switching driver circuit.

Figure 1. Single-stage LED driver

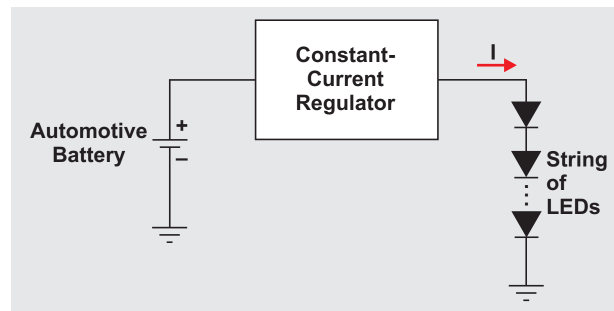


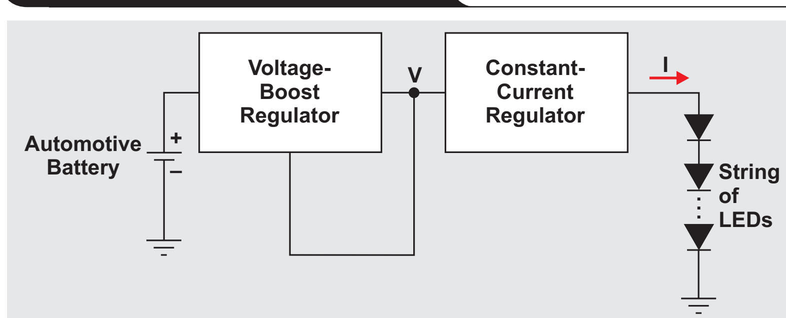
Figure 2 is a block diagram of a dual-stage LED driver circuit. The constant-current regulator, which drives current into the LED string, is not connected to the automotive battery directly. Instead, the constant-current regulator connects to the output of a voltage regulator, which in turn connects to the automotive battery.

For linear constant-current regulators, the pre-voltage regulator could be a buck, boost or buck-boost topology. For switching constant-current regulators, only a boost pre-voltage regulator makes sense. A boost topology is always required when the total LED-string forward voltage is higher than the minimum operating input voltage.

Adaptive pre-boost control

The voltage at the output of a constant-current regulator depends on the LED color—typically white, red or amber in automotive applications—and the variations of the LED

Figure 2. Dual-stage LED driver



forward-voltage characteristics. If the number of LEDs changes by N, then the voltage at the output of the constant-current regulator changes by NV_F, where V_F is the forward voltage of each LED.

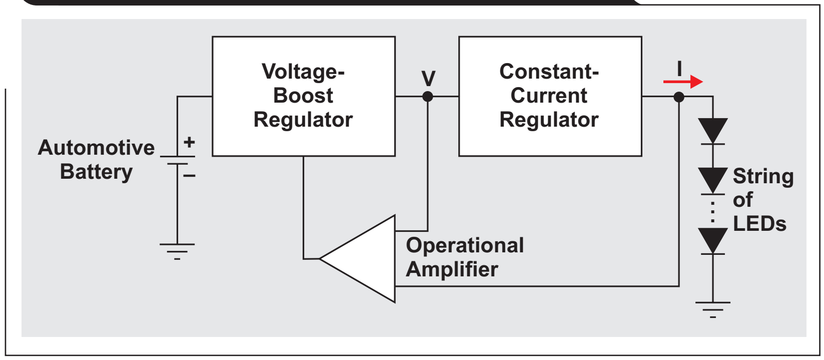
Even though the output voltage of the constant-current regulator is changing, it is possible to keep the output of the voltage-boost regulator constant. In this scenario, as the output voltage of the constant-current regulator decreases, the difference in the voltage between the input and the output of the regulator increases. If the constant-current regulator is a linear regulator, then the power dissipation increases, possibly resulting in overall lower efficiency.

Alternatively, a feedback scheme can be used to also change the output of the voltage-boost regulator based on the output of the constant-current regulator. Figure 3 shows such a scheme. Note that the voltage drop over the constant-current regulator is fed back to the voltage-boost regulator.

Using this feedback mechanism, the output of the voltage-boost regulator drops as the output of the constant-current regulator decreases. With this scheme, the difference in the voltage between the input and output of the regulator remains constant, even if its output voltage changes.

The rest of this article explores the effect of pre-boost control on the efficiency of LED driver circuits.

Figure 3. Adaptive pre-boost control using feedback from the constant-current regulator



Determining the improvement in efficiency for a linear constant-current regulator

Linear current regulators such as TI's TPS92610-Q1 drive LEDs that require low currents, such as LEDs in the rear light of a car. To infer the effect of pre-boost control on the efficiency of a complete LED driver circuit, a comparison is required between the efficiency of a circuit with pre-boost control to a circuit without pre-boost control.

In order to compare efficiency with and without pre-boost control, this article uses a white Osram LED that has the electrical parameters shown in Table 1. The values of the forward voltage in Table 1 include all forward-voltage groups of the LED.

Table 1. Electrical parameters used in the analysis

Parameter	Value
Typical LED forward voltage	$V_{F(typ)} = 3$ V
Maximum LED forward voltage	$V_{F(max)} = 3.5$ V
Minimum LED forward voltage	$V_{F(min)} = 2.5$ V
Number of LEDs in the string	N = 8
LED current	$I_{LED} = 150$ mA

First consider the LED drive circuit without pre-boost control. Designers of LED driver circuits choose the voltage output for the voltage regulator to be the sum of the worst-case LED string voltage and the worst-case dropout voltage of the linear constant-current regulator, which is assumed to be 1 V. This approach to choosing the linear constant-current regulator voltage guarantees startup for all conditions. Using the LED and linear LED driver parameters in Table 1, the pre-boost voltage is 29 V, as given by Equation 2.

$$\begin{aligned} V_{boost\_w/o} &= N \quad V_{F(max)} + V_{dropout} \\ &= 8 \quad 3.5\ \text{V} + 1\ \text{V} = 29\ \text{V} \end{aligned} \tag{2}$$

Now consider an LED driver circuit using adaptive pre-boost control, where the voltage drop on the linear constant-current regulator can be set to a fixed value, again 1 V. In the worst case, when all LEDs have the minimum forward voltage, the pre-boost voltage will be regulated to 21 V, as shown in Equation 3.

$$\begin{aligned} V_{boost\_w/} &= N \quad V_{F(min)} + V_{dropout} \\ &= 8 \quad 2.5\ \text{V} + 1\ \text{V} = 21\ \text{V} \end{aligned} \tag{3}$$

After selected the pre-boost voltage, the efficiency of the voltage regulator and linear constant-current regulator can be evaluated.

Efficiency of the pre-boost voltage regulator

To calculate the efficiency of the pre-boost voltage regulator, assume the electrical parameters shown in Table 2.

Table 2. Electrical parameters of a boost voltage regulator

Boost voltage regulator (asynchronous)	
Boost input voltage (battery voltage)	$V_{IN} = 12$ V
Switching frequency	$f_{SW\text{-}boost} = 450$ kHz
Low-side metal-oxide semiconductor field-effect transistor (MOSFET) on-resistance	$R_{DS(on)} = 0.1\ \Omega$
Switch rise/fall time	$t_r = t_f = 20$ ns
Rectifier diode forward voltage	$V_D = 0.6$ V
Inductor direct current resistance (DCR)	DCR = 40 mΩ
MOSFET output capacitance	$C_{oss} = 200$ pF
MOSFET total gate charge	$Q_g = 15$ nC

To enable calculating the total efficiency, equations in References 3 and 4 were used to calculate the power losses in the voltage regulator and the results are in Table 3. Inductor core losses are not included because they are strongly material-dependent.

Table 3. Boost-voltage regulator losses

Parameter	Without Pre-boost Control	With Pre-boost Control
Boost low-side switching losses	103 mW	54 mW
Boost low-side conduction losses	9 mW	4 mW
Boost diode losses	90 mW	90 mW
Inductor DCR losses	6 mW	3 mW
Coss losses	38 mW	20 mW
Gate driver losses	81 mW	81 mW
Boost total losses (P_{boost_loss})	**327 mW**	**252 mW**

Based on the values in Table 3, the efficiency of the boost-voltage regulator is 93.0% without pre-boost control, as shown in Equation 4, and 92.6% with pre-boost control, as shown in Equation 5.

$$\eta_{boost\_w/o} = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{29\,V \times 0.15\,A}{29\,V \times 0.15\,A + 0.327\,W} = 93.0\% \quad (4)$$

$$\eta_{boost\_w/} = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{21\,V \times 0.15\,A}{21\,V \times 0.15\,A + 0.252\,W} = 92.6\% \quad (5)$$

Efficiency of a linear constant-current regulator

Calculating the efficiency of the constant-current regulator requires evaluation of the voltage drop across the constant-current regulator without and with pre-boost control.

Without pre-boost control, the worst-case voltage drop across the linear constant-current regulator is 9 V, as shown in Equation 6.

$$V_{CCR\_drop} = V_{boost\_w/o} - N \times V_{F(min)} = 29\text{ V} - 20\text{ V} = 9\text{ V} \quad (6)$$

Based on Equation 6, the worst-case voltage drop over the constant-current regulator without pre-boost control is inferred to be 9 V, while the voltage drop with pre-boost control is 1 V. Thus, Equation 7 calculates the efficiency of the linear constant-current regulator without pre-boost control, while Equation 8 calculates the efficiency with pre-boost control.

$$\eta_{lin\_w/o} = \frac{N \times V_{F(min)}}{V_{boost\_w/o}} = \frac{20\text{ V}}{29\text{ V}} = 69.0\% \quad (7)$$

$$\eta_{lin\_w/} = \frac{N \times V_{F(min)}}{V_{boost\_w/}} = \frac{20\text{ V}}{21\text{ V}} = 95.2\% \quad (8)$$

Total circuit efficiency

Using Equations 4 and 7, the total efficiency without pre-boost control is 64.2%—see Equation 9.

$$\eta_{total\_w/o} = \eta_{boost\_w/o} \times \eta_{lin\_w/o} = 93.0\% \times 69.0\% = 64.2\% \quad (9)$$

Similarly, using Equations 5 and 8, the total efficiency with pre-boost control is 88.2%—see Equation 10.

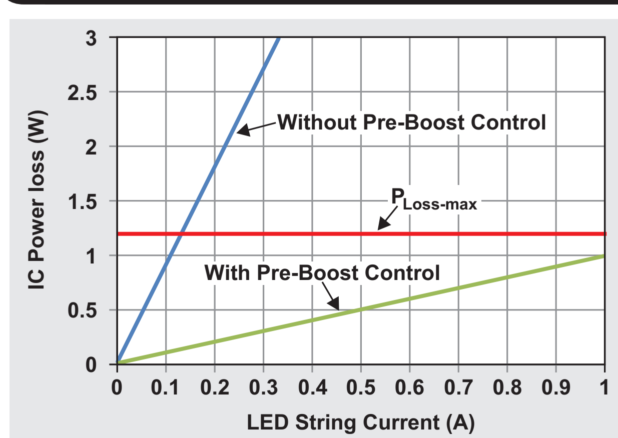
$$\eta_{total\_w/} = \eta_{boost\_w/} \times \eta_{lin\_w/} = 92.6\% \times 95.2\% = 88.2\% \quad (10)$$

These calculations show an efficiency improvement of 26% by using the adaptive pre-boost control circuit in a linear LED driver circuit. This example is based on a worst-case analysis; improvement in a real application might be lower.

Besides efficiency, adaptive pre-boost control brings an additional benefit. Figure 4 shows the power dissipation in the linear constant-current regulator across different LED string currents with and without the adaptive pre-boost control. In the figure, the red line shows the maximum allowed integrated circuit (IC) power dissipation of 1.2 W. This maximum limit is based on the typical thermal junction-to-ambient resistance of 52 °C/W in devices such as TI's TPS92610-Q1. At 85°C ambient temperature, 1.2 W is the maximum power dissipation to stay below a 150°C IC junction temperature.

Without adaptive pre-boost control, the maximum current in this configuration is limited to around 140 mA. Using adaptive pre-boost control enables current levels as high as 1,000 mA, driven by a linear constant-current regulator.

Figure 4. Power loss versus LED string current



Efficiency of the switching constant-current buck regulator

Using the same LED parameters shown in Table 1 and the voltage regulator parameters in Table 2, it is now possible to evaluate the efficiency of the voltage regulator and a switching constant-current buck regulator. Because a switching-current regulator can handle more power, the LED current can be set to 1,000 mA.

In order to calculate the efficiency of the constant-current buck regulator, assume the electrical parameters shown in Table 4.

Table 4. Electrical parameters of a constant-current buck regulator

Constant-current buck regulator (asynchronous)	
LED current	I_{LED} = 1,000 mA
Switching frequency	$f_{SW\text{-}buck}$ = 450 kHz
High-side MOSFET ON-resistance	$R_{DS(on)}$ = 0.3 Ω
Switch rise/fall time	$t_r = t_f$ = 15 ns
Rectifier diode forward voltage	V_D = 0.6 V
Inductor DCR	DCR = 60 mΩ
MOSFET output capacitance	C_{oss} = 100 pF
MOSFET total gate charge	Q_g = 10 nC

Table 5 shows the results of the power losses.

Table 5. Power losses of a constant-current buck regulator

Parameter	Without Pre-boost Control	With Pre-boost Control
Buck high-side switching losses	196 mW	142 mW
Buck high-side conduction losses	209 mW	286 mW
Buck diode losses	182 mW	28 mW
Inductor DCR losses	60 mW	60 mW
C_{oss} losses	19 mW	10 mW
Gate driver losses	130 mW	94 mW
Buck total losses ($P_{buck\_losses\_CCR}$)	**796 mW**	**620 mW**

Based on these values, the efficiency of the constant-current buck regulator is 96.2% without pre-boost control (Equation 11) and 97.0% with pre-boost control (Equation 12).

$$\eta_{buck\_w/o} = \frac{P_{out}}{P_{out} + P_{buck\_losses\_CCR}} = \frac{20\,V \times 1\,A}{20\,V \times 1\,A + 0.796\,W} = 96.2\% \quad (11)$$

$$\eta_{buck\_w/} = \frac{P_{out}}{P_{out} + P_{buck\_losses\_CCR}} = \frac{20\,V \times 0.1\,A}{20\,V \times 1\,A + 0.620\,W} = 97.0\% \quad (12)$$

Efficiency of the pre-boost voltage regulator

Table 6 shows the results of the power losses for the boost-voltage regulator.

Table 6. Power losses of a boost-voltage regulator

Parameter	Without Pre-boost Control	With Pre-boost Control
Boost low-side switching losses	491 mW	355 mW
Boost low-side conduction losses	211 mW	157 mW
Boost diode losses	430 mW	590 mW
Inductor DCR losses	141 mW	141 mW
C_{oss} losses	38 mW	20 mW
Gate driver losses	81 mW	81 mW
Boost total losses (P_{boost_losses})	1,392 mW	1,344 mW

Based on the values in Table 6, the efficiency of the boost-voltage regulator is 93.7% without pre-boost control (see Equation 4) and 93.9% with pre-boost control (see Equation 5).

Total circuit efficiency

Using Equations 4 and 11, the total efficiency without pre-boost control is 90.1% (Equation 13).

$$\eta_{total\_w/o} = \eta_{boost\_w/o} \times \eta_{buck\_w/o} = 93.7\% \times 96.2\% = 90.1\% \quad (13)$$

Similarly, using Equations 5 and 12, the total efficiency with pre-boost control is 91.1% (Equation 14).

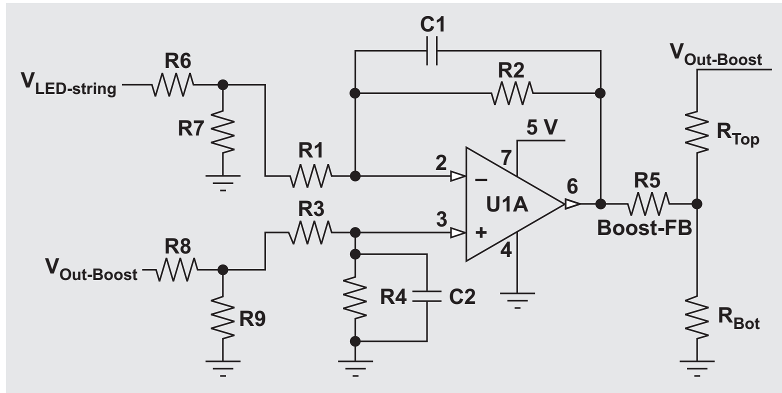
$$\eta_{total\_w/} = \eta_{boost\_w/} \times \eta_{buck\_w/} = 93.9\% \times 97.0\% = 91.1\% \quad (14)$$

These calculations clearly show almost no efficiency improvement using adaptive pre-boost control in dual-stage LED driver circuits in which the constant-current regulator is based on a switching buck topology, considering the changes in the LED's forward voltage.

Considerations for a higher switching frequency

In the analysis presented in the previous sections, the switching frequency of both regulators was 450 kHz. In systems with higher switching frequencies, like 2,200 kHz, the efficiency improvement by using pre-boost control is higher, since the pre-boost voltage and switching frequency are part of the calculation of switching losses in both regulators.

Figure 5. Adaptive pre-boost control example configuration



Pre-boost control circuit

Figure 5 shows an example configuration of an adaptive pre-boost control circuit. This circuit measures the boost voltage and voltage across the LED string. Based on the difference between these voltages—which is really the voltage across the constant-current regulator—current injected into the feedback node of the boost-voltage regulator adjusts the boost voltage based on the total LED-string forward voltage.

By choosing different input resistor-divider ratios, a certain offset can be set between the pre-boost voltage and the LED driver voltage. R1 through R4 set the gain and the combination of R5 with the feedback divider of the boost-voltage regulator sets the injection current. C1 and C2 set the bandwidth. This is important if a design requires dimming with pulse-width modulation. The response of the adaptive pre-boost control circuitry must be set slower than the pre-boost voltage regulator.

The 50-W Dual-Stage LED Driver Reference Design with Adaptive Pre-Boost Control for Automotive Headlights[5] offers more details and includes test results.

Conclusion

Using adaptive pre-boost control clearly improves efficiency in dual-stage LED driver circuits with linear constant-current regulators. There is almost no efficiency improvement if the constant-current regulator circuit is based on a switching buck topology. However, pre-boost control circuits do offer some advantages for systems with a high switching frequency.

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