Simple open-circuit protection for boost converters in LED driver applications

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Introduction

One method for driving high-brightness LEDs is to modify the standard boost-converter topology to drive a constant current through the load. However, there is a major problem with this implementation in that an open-circuit fault in the LED string removes the pathway for the load current. This creates the potential to damage the circuit due to a high-output voltage from the converter, which operates without feedback in this condition. This article presents a simple method of robust open-circuit fault protection that uses a Zener diode and a resistor with negligible changes in overall efficiency. The functionality of the topology is demonstrated by configuring a high-voltage boost converter as a constant-current driver for a string of three high-brightness white LEDs and producing a simulated fault condition at the output. The presented circuit clamps the output voltage to a safe level and reduces the output current in the protected state.

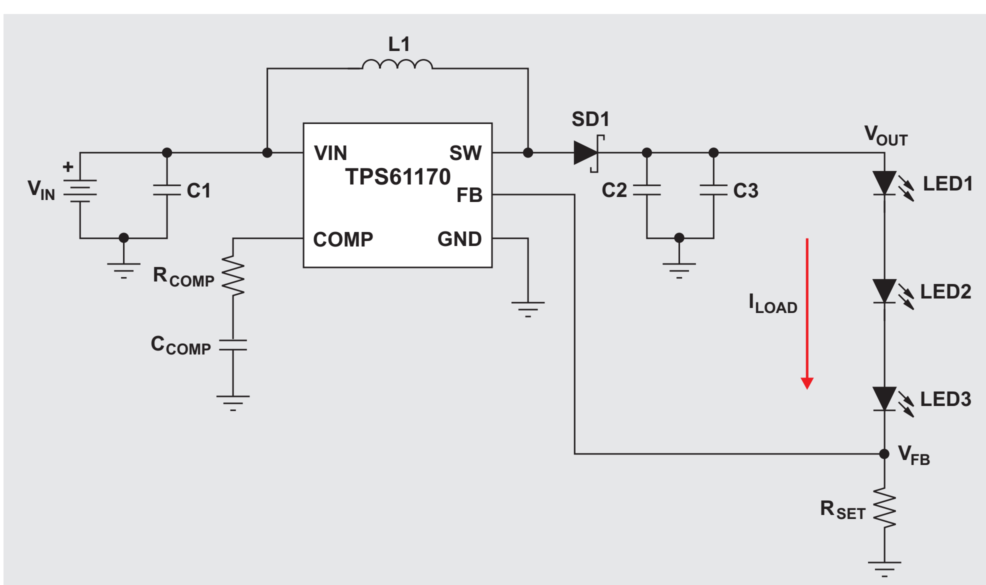
Typical boost converter for high-brightness LEDs

Boost converters are commonly modified for driving high-brightness LEDs in single-cell lithium-ion (Li-Ion), alkaline, and other applications where the voltage of the LED string exceeds the battery or rail voltage. In the standard boost configuration, the output voltage, V_{OUT}, is monitored by using a voltage divider to produce a feedback voltage, V_{FB}, for the circuit. The converter regulates the output voltage to keep V_{FB} equal to the on-chip reference voltage, V_{REF}. This topology can be adapted to maintain a constant current rather than a constant voltage by replacing the upper resistor in the feedback-voltage divider with the load, as represented by the LED string in Figure 1. The load current is dependent on the boost converter's on-chip reference voltage and is determined by

$$I_{LOAD} = \frac{V_{REF}}{R_{SET}}. \quad (1)$$

A major problem with this simple implementation is that an open-circuit fault in the LED string removes the pathway for the load current. Without the load current flowing across the feedback resistor, R_{SET}, V_{FB} is pulled to ground. In response, the boost converter increases its operating duty cycle to the maximum duty cycle possible in an effort to maintain the correct voltage on the feedback (FB) pin. Using the idealized transfer function of a boost converter reveals that a high-output voltage (V_{OUT}) can be produced when the converter approaches its maximum duty cycle. Consider a boost converter with a typical maximum duty

Figure 1. High-voltage boost converter configured as an LED driver without open-circuit protection



cycle of 90% (a common value) and a 5-V input:

$$V_{OUT} = \frac{1}{1-D} \times V_{IN} = \frac{1}{1-0.9} \times 5 = 50\ V \quad (2)$$

The high voltage at the converter's output creates the potential for multiple failures. This voltage may exceed the rating of internal or external switching devices or passive components. It may also represent a potential hazard to the user and could damage a load upon connection if the circuit is being operated without one.

Protection circuit

An alternate pathway for the load current must exist in the event of an open-circuit condition. While placing a resistor in parallel with the LED string provides a pathway, it is not ideal because it causes a significant efficiency loss. An alternative configuration (Figure 2) consists of a Zener diode and a resistor and offers suitable system protection with negligible losses in efficiency.

When the load-current pathway is removed, the output voltage increases until the Zener diode, ZD1, turns on and current flows through R_{PRO} and R_{SET} to ground. The output current is determined by the series combination of R_{PRO} and R_{SET} because V_{FB} is driven to equal the internal bandgap reference, V_{REF}. Therefore, the output protection current defaults to

$$I_{PRO} = \frac{V_{REF}}{R_{SET} + R_{PRO}}. \quad (3)$$

A voltage is chosen for the Zener diode such that no current flows through it during normal circuit operation. To ensure that the diode is completely off during normal operation, the voltage chosen should be at least 2 V higher than the maximum load voltage but still less than the maximum output voltage specified for the boost converter. This also decreases the chance that the circuit designer will have to increase the voltage rating of the output capacitors, C2 and C3, and the catch diode, SD1. The output voltage is clamped to the sum of the Zener diode's voltage and the reference voltage:

$$V_{OUT} = V_{ZD1} + V_{REF} \quad (4)$$

R_{PRO} is selected by balancing the error induced to the LED current and the power dissipated during circuit protection. In practice, the value selected for R_{PRO} should be as large as possible in order to minimize power dissipation in the Zener diode:

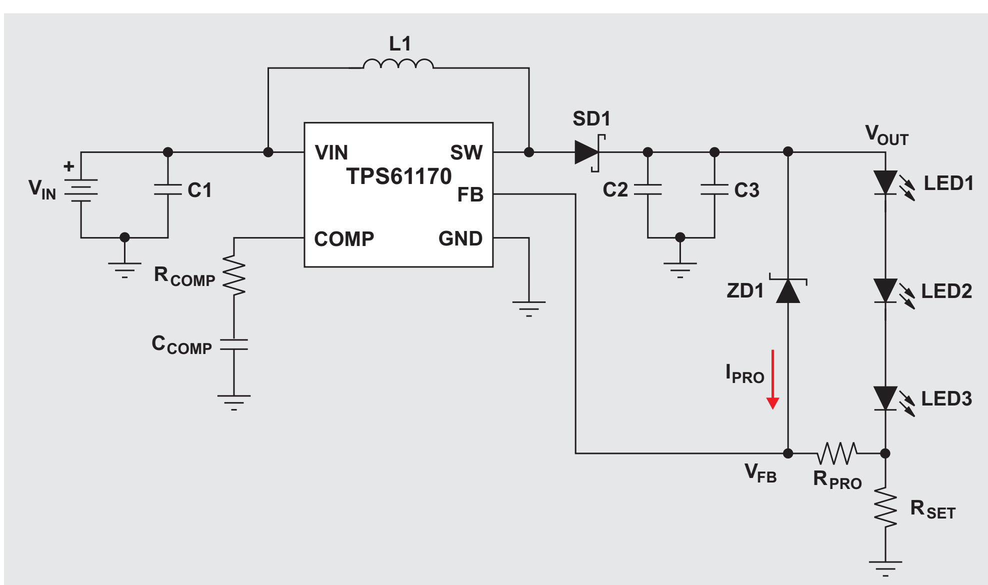
$$P_{ZD1} = I_{PRO} \times V_{ZD1} \quad (5)$$

The error introduced into the circuit is due to the leakage current through the Zener diode, I_{ZL}, as well as the bias current, I_{FB}, of the error amplifier internal to the boost converter. Equation 6 is a revised transfer function that includes these errors:

$$I_{LOAD} = \frac{V_{REF} - I_{ZL}(R_{PRO} + R_{SET}) - I_{FB}(R_{PRO} + R_{SET})}{R_{SET}} \quad (6)$$

Because these two currents are normally less than 1 µA, the error introduced is very small and can be ignored in most implementations.

Figure 2. LED driver circuit with open-circuit protection

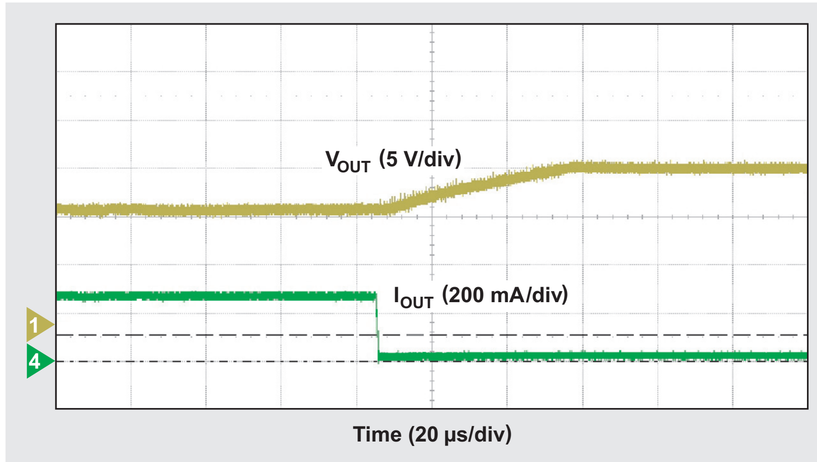


Demonstration

As an application example, the Texas Instruments TPS61170 boost converter IC was configured as a constant-current LED driver. This is an ideal boost converter for driving a string of high-brightness LEDs in applications such as backlighting or flashlights. The 3- to 18-V input range allows a wide range of power sources, such as 2S-to-4S Li-Ion or 3S-to-12S alkaline battery packs, USB, or 12-V rail power.

The boost converter was configured to drive three high-brightness white LEDs with a current of 260 mA. With a typical reference voltage of 1.229 V, R_{SET} was calculated by using the simplified version of the load current in Equation 7:

Figure 3. Oscilloscope screen shot of protection-circuit activation



$$R_{SET} = \frac{V_{REF}}{I_{LOAD}} = \frac{1.229\ \text{V}}{260\ \text{mA}} = 4.73\ \Omega \qquad (7)$$

A value of 1 mA was chosen as a reasonable protection current (I_{PRO}) to calculate the value of R_{PRO}:

$$R_{PRO} = \frac{V_{REF}}{I_{PRO}} - R_{SET} = \frac{1.229\ \text{V}}{1\ \text{mA}} - 4.7\ \Omega = 1224.3\ \Omega \rightarrow 1.2\ \text{k}\Omega \qquad (8)$$

A 15-V Zener diode was chosen for ZD1 in order to exhibit minimal leakage at the expected load voltage of approximately 10 V, while also clamping the output to a value far below the maximum allowable output voltage of the boost converter, 40 V. The output voltage was clamped to the Zener diode's voltage (V_{ZD1}), which was summed with the converter's reference voltage:

$$V_{OUT} = V_{ZD1} + V_{REF} = 15\ \text{V} + 1.229\ \text{V} = 16.229\ \text{V} \qquad (9)$$

With the load current and protection resistors selected, the deviation from the expected load current was calculated (see Equation 10 below). The datasheet value of 200 nA was used for the feedback bias current (I_{FB}), and a value of 1 µA was used for the expected leakage current through the Zener diode, with a V_{OUT} of approximately 10 V.

Recall that the intended load current for the circuit was 260 mA. As can be seen, once the theoretical values for components are replaced by available values in Equation 10, they contribute far more error than does the protection circuit itself.

To test the protection circuit's operation, the LED string was replaced with a resistor decade box set to 38 Ω to mimic the voltage across the LED string at the designed load current. An open-circuit fault was simulated by rapidly changing the load resistance from 38 Ω to 1038 Ω. As illustrated in Figure 3, the change in the output current (green trace) signaled the sudden change in load impedance. To compensate, the output voltage of the TPS61170 (yellow trace) rose to re-establish the designed load current. However, rather than continuing this trend until reaching its maximum duty cycle, the output voltage stabilized to the clamp voltage of approximately 16 V.

Conclusion

A simple method to provide open-circuit protection to a boost converter configured as a constant-current LED driver was presented. Consisting of a Zener diode and an additional resistor, this circuit limits the output voltage to a safe level while simultaneously reducing the output current when an open-circuit fault occurs at the load. Furthermore, this approach contributes negligible error to the load-current calculations and negligible loss of efficiency during normal circuit operation. The functionality of the protection circuit was demonstrated by configuring a boost converter as an LED driver and adding a 15-V Zener diode and a 1.2-kΩ resistor for output protection. The demonstration circuit exhibited the expected output behavior in a simulated load fault condition.

Related Web sites

power.ti.com
www.ti.com/product/TPS61170

$$I_{LOAD} = \frac{1.229\ \text{V} - 1\ \mu\text{A}(1.2\ \text{k}\Omega + 4.7\ \Omega) - 200\ \text{nA}(1.2\ \text{k}\Omega + 4.7\ \Omega)}{4.7\ \Omega} = 261\ \text{mA} \qquad (10)$$

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