ABSTRACT

Single light-emitting diode (LED) functions like backlight and lighting are widely used in AA battery (alkaline) powered systems such as portable electronic device or sensors. This application report mainly focuses on ultra-low $V_{IN}$, ultra-low $I_{O}$, true shut down, and pulse-width modulation (PWM) dimming functions, all for which the TPS61021A serves as a good LED driver. This report also addresses how to use the TPS61021A and some of the important considerations to make.
1 Application Requirements

1.1 Ultra-Low Input Voltage
Single AA battery-powered applications must have an input voltage as low as 0.9 V, which requires a boost topology. In certain cases, designers can use two AA batteries in series to power the system microcontroller (MCU), thus making the minimum $V_{IN}$ as low as 1.8 V. The voltage of a single new AA battery is approximately 1.6 V; therefore, the LED driver $V_{IN}$ range must cover 0.9 V to 3.2 V to support both one- and two-AA battery configurations.

1.2 True Shutdown Function
Under typical circumstances, boost converters are not capable of shutting down the output after being disabled, which is especially true for an asynchronous converter. However, the LED drive application requires a true shutdown function to turn off the LED after it has been disabled. A true shutdown function is also required for shorts and thermal protection.

1.3 PWM Dimming
Some backlight applications require a PWM dimming function. The typical duty cycle is from 10% to 100% with a 100-Hz frequency. The minimal $T_{ON}$ time is approximately 1 ms. For most switching converters, a slow soft-start function is a requirement to reduce the inrush current. Note that the EN pin may not be suitable for this dimming if the start-up is too slow.

1.4 Quiescent Current ($I_Q$) and Shutdown Current ($I_{SD}$)
The total system must be less than 20 µA to maximize the battery lifetime. $I_Q$ and $I_{SD}$ must both be as low as possible. The $I_{SD}$ value is more important and it must be less than 1 µA when disabled.

1.5 Forward Current ($I_F$) and Forward Voltage ($V_F$)
The forward current ($I_F$) of an LED may be high in lighting mode (up to 100 mA) and low (down to 5 mA) in indicating mode. The forward voltage ($V_F$) varies based on the different colors of an LED; white LEDs typically have a higher $V_F$ (2.7 V to 3.5 V). The value for $V_F$ changes with the driving current as well as temperature.

1.6 Accuracy and Efficiency
A 10% current accuracy is acceptable for most applications. The efficiency has a direct relation to $I_Q$ and $I_{SD}$. The headroom voltage and the efficiency typically vary based on the usage condition.

1.7 Working Temperature
The working temperature is typically specified for portable or home devices. For example, a 0°C to 60°C temperature is suitable for most devices.
2 Single LED Boost Drive Circuit

2.1 Why Choose TPS61021A?

The TPS61021A offers the following features:
- Large \( V_{\text{IN}} \) range: 0.5 V to 4.4 V covers 0.9 V to 3.2 V
- Low \( I_Q \) and \( I_{SD} \): 17 µA and 0.5 µA
- True disconnect function: Internal PMOS can shut down when disabled
- Quick soft start: 200 µs; can support minimal 10% duty cycle with a 100-Hz specification
- High current accuracy: 1.8% accuracy \( V_{\text{FB}} \) builds a sufficient constant current source

Figure 1 shows the internal block diagram of the TPS61021A.

Figure 1. TPS61021A Internal Block Diagram
2.2 Single LED Drive Circuit

The circuit in Figure 2 has great current accuracy. The $V_{OUT}$ is 3.2 V to 4.2 V, which means that the boost always works when in boost mode and has good efficiency. When the $V_{IN}$ is specified from 1.8 V to 3.6 V, the efficiency is above 85% with an 8-mA load (see Figure 3).

![Figure 2. Direct Drive With FB Network](image)

![Figure 3. Load Efficiency With Different $V_{IN}$](image)
The PWM dimming function through the enable pin works well and allows the user to easily change the duty cycle from 10% to 90% (see Figure 4, Figure 5, and Figure 6).

**Figure 4. 10% Duty Cycle**

**Figure 5. 50% Duty Cycle**
The single LED drive circuit is very capable of using the EN pin for dimming (see Figure 7).

Blue = Enable PWM Signal
Green = LED Current Signal

Figure 6. 90% Duty Cycle

Figure 7. Figure 4. PWM Dimming and True Disconnect
3 Design Considerations

3.1 \( V_F \) Variety and Temperature Drift

From the manufacturing process, the \( V_F \) value of the LED follows the Gauss distribution. Table 1 shows that the \( V_F \) range is from 2.7 V to 3.5 V when the \( I_F \) is set to 20 mA in a typical LED specification. The \( V_F \) also changes with \( I_F \) and temperature, as Figure 8 and Figure 9 show. The \( V_F \) must have an approximate 0.2-V additional drift at the full temperature.

Table 1. \( V_F \) Bins Voltage Range

<table>
<thead>
<tr>
<th>GROUP</th>
<th>BIN</th>
<th>MIN</th>
<th>MAX</th>
<th>UNIT</th>
<th>CONDITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>10</td>
<td>2.70</td>
<td>2.90</td>
<td>V</td>
<td>( I_F = 20 \text{ mA} ) ( T = 25 \text{°C} )</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>2.90</td>
<td>3.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>3.10</td>
<td>3.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>3.30</td>
<td>3.50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 8. \( V_F \) versus \( I_F \)](image)

![Figure 9. \( V_F \) versus Temperature](image)

Consider all the possible \( V_F \) bins at the full temperature range from 0°C to 60°C, as calculated in the following three equations.

1. \( V_F = 8 \text{ mA} \) = \( V_{F_r} = 20 \text{ mA} - R_{AC} \times (20 \text{ mA} - 8 \text{ mA}) \approx V_{F_r} = 20 \text{ mA} - 0.2 \text{ V} \)

\[ 2.4 \text{ V} = V_{F_r} = 8 \text{ mA} \text{ at } \text{BIN}_{10_{\text{max}}} \text{ at } 60°C \]

\[ = V_{F_r} = 20 \text{ mA at } \text{BIN}_{10_{\text{max}}} \text{ at } 25°C - R_{AC} (20 \text{ mA} - 8 \text{ mA}) - K_T (60°C - 25°C) \]

\[ = 2.7 \text{ V} - 0.216 - 0.084 \]

2. \( 3.4 \text{ V} = V_{F_r} = 8 \text{ mA} \text{ at } \text{BIN}_{13_{\text{max}}} \text{ at } 0°C \)

\[ = V_{F_r} = 20 \text{ mA at } \text{BIN}_{13_{\text{max}}} \text{ at } 25°C - R_{AC} (20 \text{ mA} - 8 \text{ mA}) + K_T (25°C - 0°C) \]

\[ = 3.5 \text{ V} - 0.216 + 0.118 \]

The \( V_F \) range is approximately 2.5 V to 3.3 V when \( I_F \) is 8 mA. Accounting for temperature drift, the full range of \( V_F \) is approximately 2.4 V to 3.4 V, which is within the normal \( V_F \) range for an LED backlight application.
3.2 LDO Mode When $V_{OUT}$ is Low

The LED driver always works in boost mode for a single AA battery-powered system, where the accuracy is always good and the efficiency is high. However, conditions may vary when using two AA batteries in-series to power a system.

In a two AA battery system, the $V_{IN}$ is 1.8 V to 3.2 V. The $V_{OUT}$, which is $V_F$ plus $V_{FB}$, may be lower than $V_{IN}$ when the $I_F$ is low or the temperature is high. This relationship means that using LDO mode is necessary to continue regulating $V_{OUT}$ and maintain current accuracy; however, doing so decreases efficiency. Alternatively, if the $V_{FB}$ is too low (such as 0.2 V), then the $V_{OUT}$ is somewhere between 2.6 V to 3.4 V. This condition requires using LDO mode. The low-pass mode is another option but it features lower accuracy.

The $V_{FB}$ of the TPS61021A device is high (up to 0.8 V). Use a range of 2.4 V to 3.4 V for the $V_F$ to ensure that the TPS61021A device always works in boost mode. When using a two AA battery-powered system, be sure to make $V_{OUT}$ larger than $V_{IN}$ to obtain good accuracy and efficiency.

3.3 Adjust $V_{FB}$ When $V_{OUT}$ is High

When the LDO works on the high $I_F$ and low temperature, the $V_{OUT}$ may extend the output range of the driver and trigger overvoltage protection (OVP). The data sheet for the TPS61021A notes that the maximum for $V_{OUT}$ is 4.0 V and the typical OVP is approximately 4.35 V. If the user is driving the LED with a high $I_F$ and low temperature, then the $V_{OUT}$ may be out of range. In this situation, adjust to a lower $V_{FB}$ to make sure the $V_{OUT}$ remains in range.

The user can choose from three methods for adjusting the $V_{FB}$ to a lower value.

1. Use a low-noise-voltage-source low-dropout regulator (LDO) or $V_{REF}$ as the $V_{ADJUST}$ (see Figure 10 side A).

2. Use an additional amplifier if the system must reduce the $V_{FB}$ (see Figure 10 side B).

3. Use an R-divider to make the trade-off between accuracy and cost.

If an additional $V_{ADJUST}$ or amplifier is not available in the system, make a trade-off with current accuracy to simply adjust the $V_{FB}$ and save on costs. As Figure 11 shows, the $V_{OUT}$ can function as the $V_{ADJUST}$.
Figure 11. Using External Resistor Divider

1. Set the $V_{\text{SET}}$ voltage and $I_F$; for example, set $V_{\text{SET}} = 0.6$ V and $I_F = 8$ mA.
Choose the following values for the LED bin: $V_F$ at 20 mA = 3.2 V, $R_{AC} = 18$ Ω (see Equation 4).

$$V_{FB} = V_{FB} - \frac{(V_{\text{ADJUST}} - V_{FB}) R2}{R3}; \quad I_{LED} = \frac{V_{FB}}{R1} \frac{V_{\text{ADJUST}} - V_{FB}}{R2}$$

(4)

2. Choose the values for $R3$ according to the $V_{\text{SET}}$ and $I_F$ values: $R3 = 75$ Ω for $V_{\text{SET}} = 0.6$ V and $I_F = 8$ mA.

3. Choose the values for $R2$ and $R1$ (see Equation 5):

$$V_{FB} = V_{FB} \cdot I_{LED} = \frac{V_{FB}}{GvR1}$$

Take $R2 = 100$ kΩ; $R1 = 1.3$ MΩ.

(5)

4. Calculate the $I_F$ accuracy change using a different bin $V_F$ at 20 mA (see Equation 6).

$$V_F \text{ at } 8 \ mA = V_F \text{ at } 20 \ mA + \frac{R_{AC}(8-20)}{1000} = 3.2 - 18 \times \frac{12}{1000} = 2.984 \text{ V}$$

(6)

A lower $V_{FB}$ adjustment results in larger error. The histogram in Figure 12 shows this trend. A 10% current accuracy can be a trade-off for applications where ultra-low-power is critical. Use this method to reduce the $V_{FB}$ to 0.5 V. TI does not recommend setting a lower $V_{FB}$ due to the resulting bad accuracy.
Design Considerations

Figure 12. Error Trend With Lower $V_{FB}$
4 Summary

TPS61021A offers a great solution as a single LED drive circuit in AA battery-powered systems. Be sure to account for problems, such as a $V_{\text{OUT}}$ that fluctuates too low or too high, to ensure a sufficient level of efficiency and accuracy.

5 References

1. Texas Instruments, *TPS61021A 3-A Boost Converter with 0.5-V Ultra Low Input Voltage*, TPS61021A Data Sheet (SLVSDM0)
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