**TI Designs: TIDA-01234**

**24-W Boost and Boost-to-Battery Reference Design for Automotive LED Lighting**

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**Description**

This reference design is a 24-W, high-efficiency (94%), low-cost, asynchronous boost design for automotive LED applications based on the LM3481-Q1.

**Features**

- 24-W Automotive LED Driver Solution
- Input: 6 to 18 V, Output: 24 V at 1 A for Boost and \( V_{\text{IN}} + 12 \) V at 1 A for Boost to Battery
- 94% System Efficiency at Full Load at 12 \( V_{\text{IN}} \) for Boost
- 88.9% System Efficiency at Full Load at 12 \( V_{\text{IN}} \) for Boost to Battery
- Switching Frequency: 350 kHz
- 0- to 1-A Full Range Analog Dimming
- Open Circuit Protection

**Applications**

- SMPS for Automotive LED Lighting

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**Resources**

- **TIDA-01234** Design Folder
- **LM3481-Q1** Product Folder
- **INA213-Q1** Product Folder

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**An IMPORTANT NOTICE** at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.
1 System Description

This reference design is a 24-W, high-efficiency, low-cost, asynchronous boost design for automotive LED applications based on the LM3481-Q1. This design applies to automotive high brightness lighting such as headlights, tail lights, and interior LED lighting systems. The design also support analog LED brightness control and output open protection.

The design is divided into two major configurations:

1. Boost configuration:
   - Wide input range from 6 to 18 V_{IN}
   - Can drive multiple strings of six to seven LEDs at 1-A constant current
   - High efficiency (94%), low cost

2. Boost-to-battery configuration:
   - Wide input range from 6 to 18 V_{IN}
   - Input voltage can either be higher, lower, or equal to required LED strings voltage
   - High efficiency (89%), low cost

1.1 Key System Specifications

Table 1. Key System Specifications

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{IN} minimum</td>
<td>6 V DC</td>
</tr>
<tr>
<td>V_{IN} maximum</td>
<td>18 V DC</td>
</tr>
<tr>
<td>V_{OUT}</td>
<td>16 to 24 V (boost only), 8 to 12 V (boost-to-battery)</td>
</tr>
<tr>
<td>LED drive current (maximum)</td>
<td>1 A</td>
</tr>
<tr>
<td>Approximate switching frequency</td>
<td>350 kHz</td>
</tr>
<tr>
<td>LED dimming</td>
<td>0 to 1 A with no flickering</td>
</tr>
</tbody>
</table>
2 System Overview

2.1 Block Diagram

TIDA-01234
24W Boost and Boost-to-Battery Reference Design for Automotive LED Lighting

Figure 1. TIDA-01234 Block Diagram
Figure 2. Automotive LED Lighting Example Highlighting TIDA-01234
2.2 **Highlighted Products**

The following TI products are used in this reference design.

2.2.1 **LM3481-Q1**
- AEC-Q100 grade 1 qualified temperature: –40°C to 125°C operating junction temperature
- Wide supply voltage range: 2.97 to 48 V
- 100-kHz to 1-MHz adjustable and synchronizable clock frequency
- Pulse skipping at light loads
- Adjustable undervoltage lockout (UVLO) with hysteresis
- Internal soft-start

2.2.2 **INA213-Q1**
- AEC-Q100 grade 1 qualified temperature: –40°C to 125°C operating junction temperature
- Wide common-mode range: –0.3 to 26 V
- Offset voltage: ±100 μV (maximum; enables shunt drops of 10-mV full-scale)
- Accuracy:
  - ±1% gain error (maximum over temperature)
  - 0.5-μV/°C offset drift (maximum)
  - 10-ppm/°C gain drift (maximum)
- Quiescent current: 100 μA (maximum)
- SC70 package
2.3 System Design Theory

2.3.1 Boost Description

Generally, the output voltage can be programmed using a resistor divider and feedback pins. The output current depends on the load requirement. But for an LED application, constant current is necessary to keep a specific lightness. This design used current sensing to achieve constant current by the boost controller LM3481-Q1.

To keep constant current flowing through LED, there is a current sense resistor, $R_{SHUNT}$, at the output of the controller to sense how much current flows through it. This reference design uses a 50-mΩ current sense resistor to generate 50 mV of crossing voltage. This crossing voltage will be amplified by the INA213-Q1, which provides a gain = 50 V/V. Using an external voltage injected into the current sense amplifier reference at J1 allows for analog dimming of the LEDs at the output by changing the output current, as shown in Equation 1:

$$V_{FB} = \left( \left( I_{OUT} \times R_{SHUNT} \right) + V_{REF} \right) \times \frac{R3}{R3 + R4}$$

(1)

where:

- $V_{FB}$ is 1.275 V
- $R_{SHUNT}$ is 50 mΩ
- $R3$ equal to $R4$ are 10 kΩ

If the output LED burns out or is open at the output circuit, the output voltage will continuously rise. The TIDA-01234 design provides output open circuit protection. For the boost configuration, a Zener diode connected between $V_{OUT}$ and $V_{FB\_DIV}$, clapping the output voltage at the Zener voltage $V_z$ plus the output voltage of the current sense amplifier.

Figure 3. Boost Configuration and LM3481 Schematic
2.3.2 Boost-to-Battery Description

In order to generate constant current with an output voltage closed to the input voltage, the designer must use a buck-boost or a SEPIC structure, which is complex and costly. By connecting the cathode of LED strings to the input instead of the GND, the TIDA-01234 can also be modified to boost-to-battery configuration. In this configuration, input voltage can either be higher, lower, or equal to the required LED strings voltage.

![Boost-to-Battery Configuration and LM3481 Schematic](image)

For boost-to-battery, the TIDA-01234 provides another solution for open circuit protection by using transistor Q2 combined with R5, R6, R7, R8, and D2 to detect differential voltage between output voltage and input voltage. When the differential voltage rises up to $V_{OV}$, where $V_{OV}$ is overvoltage at the output, Zener diode D2 will turn on and pull the comp pin voltage down by Q3. As a result, the output voltage will stay low until the load is connected.

For design calculations and layout examples, see the devices' respective datasheets:

- LM3481-Q1 High-Efficiency Controller for Boost, SEPIC and Flyback DC-DC Converters (SNVS346)
- INA21x-Q1 Automotive-Grade, Voltage Output, Low- or High-Side Measurement, Bidirectional, Zero-Drift Series, Current-Shunt Monitors (SBOS475)
3 Testing and Results

3.1 Boost Configuration Test Results

3.1.1 Thermal Data

The infrared thermal image shown in Figure 5 was taken at a steady state with 12 V\textsubscript{IN} and full load of a 1-A load current (current sense comparator reference set to 0 V) for boost configuration.

![Image of thermal image](image)

Figure 5. Thermal Image of Boost Configuration

3.1.2 Efficiency Data

3.1.2.1 Efficiency Chart

![Image of efficiency chart](image)

Figure 6. Boost Efficiency versus Load Current at Various Input Voltages
### 3.1.2.2 Efficiency Data

**Table 2. Boost Efficiency Table at 6 V\textsubscript{IN}**

<table>
<thead>
<tr>
<th>REF (V)</th>
<th>V\textsubscript{IN} (V)</th>
<th>I\textsubscript{IN} (A)</th>
<th>V\textsubscript{OUT} (V)</th>
<th>I\textsubscript{OUT} (A)</th>
<th>EFF (%)</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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**Table 3. Boost Efficiency Table at 10 V\textsubscript{IN}**

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<tr>
<th>REF (V)</th>
<th>V\textsubscript{IN} (V)</th>
<th>I\textsubscript{IN} (A)</th>
<th>V\textsubscript{OUT} (V)</th>
<th>I\textsubscript{OUT} (A)</th>
<th>EFF (%)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
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<td>2.564</td>
<td>24.11</td>
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<td>94.92563</td>
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<td>1.0</td>
<td>10.006</td>
<td>1.251</td>
<td>22.17</td>
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<td>0.002</td>
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**Table 4. Boost Efficiency Table at 12 V\textsubscript{IN}**

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<th>REF (V)</th>
<th>V\textsubscript{IN} (V)</th>
<th>I\textsubscript{IN} (A)</th>
<th>V\textsubscript{OUT} (V)</th>
<th>I\textsubscript{OUT} (A)</th>
<th>EFF (%)</th>
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**Table 5. Boost Efficiency Table at 15 V\textsubscript{IN}**

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<tr>
<th>REF (V)</th>
<th>V\textsubscript{IN} (V)</th>
<th>I\textsubscript{IN} (A)</th>
<th>V\textsubscript{OUT} (V)</th>
<th>I\textsubscript{OUT} (A)</th>
<th>EFF (%)</th>
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</tbody>
</table>
3.1.3 Boost Configuration Waveforms

3.1.3.1 Switching and Output Current

**Figure 7.** 12-V$_{IN}$ and 0-V Reference on Current Sense Comparator Provides Maximum Output Current

**Figure 8.** 12 V$_{IN}$ and 1.2-V Reference on Current Sense Comparator Provides Maximum Output Current

**Figure 9.** 12 V$_{IN}$ and 2.5-V Reference on Current Sense Comparator Provides Maximum Output Current

**NOTE:** Ch1 (yellow trace): Switch node voltage, Ch2 (pink trace): Output current
3.1.3.2 System Startup Waveforms

Figure 10. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 9 V\textsubscript{IN}

Figure 11. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 9 V\textsubscript{IN}

Figure 12. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 12 V\textsubscript{IN}

Figure 13. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 12 V\textsubscript{IN}
3.1.4 Analog Dimming

NOTE: Figure 16 shows the current regulation for the boost configuration.
3.1.5 Loop Response

**Figure 17.** 6-V\textsubscript{IN} Loop Response Showing a Stable System With Gain Margin: 13.8 dB and Phase Margin: 86.5°

**Figure 18.** 12-V\textsubscript{IN} Loop Response Showing a Stable System With Gain Margin: 11.4 dB and Phase Margin: 71.4°
3.2  Boost-to-Battery Configuration Test Results

3.2.1  Thermal Data

The infrared thermal image shown in Figure 19 was taken at steady state with 12 V\textsubscript{IN} and full load of a 1-A load current (current sense comparator reference set to 0 V) for boost-to-battery configuration.

![Figure 19. Thermal Image of Boost-to-Battery](image)

3.2.2  Efficiency Data

3.2.2.1  Efficiency Chart

![Figure 20. Boost-to-Battery Efficiency versus Load Current at Various Input Voltages](image)
### 3.2.2.2 Efficiency Data

#### Table 6. Boost-to Battery Efficiency Table at 6 $V_{IN}$

<table>
<thead>
<tr>
<th>REF (V)</th>
<th>$V_{IN}$ (V)</th>
<th>$I_{IN}$ (A)</th>
<th>$V_{OUT}$ (V)</th>
<th>$I_{OUT}$ (A)</th>
<th>EFF (%)</th>
</tr>
</thead>
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<td>0</td>
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</table>

#### Table 7. Boost-to Battery Efficiency Table at 10 $V_{IN}$

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<thead>
<tr>
<th>REF (V)</th>
<th>$V_{IN}$ (V)</th>
<th>$I_{IN}$ (A)</th>
<th>$V_{OUT}$ (V)</th>
<th>$I_{OUT}$ (A)</th>
<th>EFF (%)</th>
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#### Table 8. Boost-to Battery Efficiency Table at 12 $V_{IN}$

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<th>$V_{IN}$ (V)</th>
<th>$I_{IN}$ (A)</th>
<th>$V_{OUT}$ (V)</th>
<th>$I_{OUT}$ (A)</th>
<th>EFF (%)</th>
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#### Table 9. Boost-to Battery Efficiency Table at 15 $V_{IN}$

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<th>REF (V)</th>
<th>$V_{IN}$ (V)</th>
<th>$I_{IN}$ (A)</th>
<th>$V_{OUT}$ (V)</th>
<th>$I_{OUT}$ (A)</th>
<th>EFF (%)</th>
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</thead>
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</tbody>
</table>
3.2.3 Boost-to-Battery Configuration Waveforms

3.2.3.1 Switching and Output Current

NOTE: Ch1 (yellow trace): Switch node voltage, Ch2 (pink trace): Output current
3.2.3.2 System Startup Waveforms

Figure 24. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 9 $V_{IN}$

Figure 25. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 9 $V_{IN}$

Figure 26. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 12 $V_{IN}$

Figure 27. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 12 $V_{IN}$
3.2.4 Analog Dimming

Figure 30. Reference Voltage for Current Sense Comparator versus Load Current

NOTE: Figure 30 shows the current regulation for the boost configuration.
3.2.5 Open Circuit Protection

Figure 31. Boost-to-Battery Open Circuit Protection
3.2.6 Loop Response

**Figure 32. 6-V \( V_{in} \) Loop Response Showing a Stable System With Gain Margin: 10.0 dB and Phase Margin: 93.95°**

**Figure 33. 12-V \( V_{in} \) Loop Response Showing a Stable System With Gain Margin: 8.9 dB and Phase Margin: 99.7°**
4 Design Files

4.1 Schematics
To download the schematics, see the design files at TIDA-01234.

4.2 Bill of Materials
To download the bill of materials (BOM), see the design files at TIDA-01234.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints
To download the layer plots, see the design files at TIDA-01234.

4.4 Altium Project
To download the Altium project files, see the design files at TIDA-01234.

4.5 Gerber Files
To download the Gerber files, see the design files at TIDA-01234.

4.6 Assembly Drawings
To download the assembly drawings, see the design files at TIDA-01234.

5 Software Files
To download the software files, see the design files at TIDA-01234.

6 Related Documentation
This reference design did not use any related documentation.

6.1 Trademarks
All trademarks are the property of their respective owners.

7 About the Author
SHAQUILLE CHEN is a field application engineer at Texas Instruments where he is responsible for major account in Taiwan. Shaquille earned his master of technology (M.Tech) from the National Taiwan University of Science and Technology in Taipei.
## Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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<thead>
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<th>Changes from Original (August 2016) to A Revision</th>
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<tbody>
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<td>• Changed from preview draft to fit current design guide template.</td>
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