**TI Designs**

**Automotive eCall Reference Design**

**TI Designs**

TIDA-00159 is a reference design for vehicles equipped with eCall systems. TIDA-00159 has the capability to enable phone calls to an emergency service center in the event of an accident. Customers may accelerate the design of their eCall systems by taking advantage of a complete reference design comprising analog AEC-Q100 qualified integrated circuits (ICs) from TI. This design creates a robust, low-cost solution that is scalable. The design has flexible power operations, which allows the system to be powered from the main car battery or the backup cell battery.

**Design Resources**

- **TIDA-00159** Design Folder
- **CSD18532Q5B** Product Folder
- **CSD18534Q5A** Product Folder
- **MSP430F2232** Product Folder
- **TPS43330-Q1** Product Folder
- **TPS7A1601-Q1** Product Folder
- **TRS3223-Q1** Product Folder
- **TAS5421-Q1** Product Folder

**Design Features**

- The TPS43330-Q1 Pre-Boost Circuit Supports Automotive Start and Stop
- Boosts Backup Battery Supply Voltage, Allowing Operation Down to 2 V at Input
- TAS5421-Q1 Delivers 10 W of Output Power at 8 Ω, Resulting in Clear and Loud Audio
- Audio Amplifier Features Integrated Diagnostics to Increase Safety Level
- Provides Load Dump Protection Against Input Transients up to 40 V
- Sustains 10- to 15-Minute Phone Call in Emergency Situations
- Compatible With Sierra Wireless AirLink FX100; Can Directly Connect to TIDA-00159 and Programmable Through Set of AT Commands

**Featured Applications**

- Automotive Emergency Call and Telematics

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Table 1 lists the key system specifications.

### Table 1. Key System Specifications

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
<th>DETAILS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>12-V nominal</td>
<td>Section 7.1, Section 7.2</td>
</tr>
<tr>
<td></td>
<td>4.5- to 40-V DC</td>
<td></td>
</tr>
<tr>
<td>Interface</td>
<td>RS-232</td>
<td>Section 4.4</td>
</tr>
<tr>
<td>RS-232 DSub15 connector</td>
<td>DSub 15 connector</td>
<td>Section 4.4</td>
</tr>
</tbody>
</table>
The TIDA-00159 is an emergency call (eCall) system reference design that has the capability to enable phone calls to an emergency service center in the event of an accident. This design has an input OR-ing scheme that enables the use of a 12-V adapter or utilizes a LiFePO4 backup battery in the case of a disconnection from the main 12-V supply. The AEC-Q100 one-boost, two-buck, power management IC (PMIC) and low drop-out regulators (LDO) are able to sustain all the voltage rails required for the TI MSP430™ microcontroller (MCU), RS232 transceiver, and class-D audio amplifier. The MSP430, which has been designed to be compatible with the Sierra Wireless FX100 Modem, uses AT commands to communicate through a Dsub-15 connector to instantiate functions that enable the phone calls, in addition to enabling the backup battery to charge, switch on, and power the system.

Figure 1 shows the automotive eCall reference design.

![Automotive eCall Reference Design](image-url)
3 Block Diagram

Figure 2. Automotive eCall Block Diagram
3.1 **Highlighted Products**

3.1.1 **TPS43330-Q1 Automotive, Low I\textsubscript{Q}, Single-Boost, Dual-Synchronous Buck Controller PMIC**

The TPS43330-Q1 and TPS43332-Q1 devices (TPS4333x-Q1) include two current-mode synchronous buck controllers and a voltage-mode boost controller. The TPS4333x-Q1 family of devices is ideally suited as a pre-regulator stage with low I\textsubscript{Q} requirements and for applications that must survive supply drops as a result of cranking events. The integrated boost controller allows the devices to operate down to 2 V at the input without experiencing a drop on the buck regulator output stages. At light loads, the buck controllers can be enabled to operate automatically in low-power mode, consuming just 30 µA of quiescent current.

The buck controllers have independent soft-start capability and power-good indicators. Current foldback in the buck controllers and cycle-by-cycle current limitation in the boost controller provide external MOSFET protection. The switching frequency can be programed over 150 kHz to 600 kHz or synchronized to an external clock in the same range. Additionally, the TPS43332-Q1 device offers frequency-hopping spread-spectrum operation.

**Figure 3. Typical Application Diagram**
Figure 4. TPS43330-Q1 Functional Block Diagram
3.1.2 TAS5421-Q1 22-W Mono Automotive Digital Amplifier With Load Dump and I²C Diagnostics

The TAS5421-Q1 is a mono digital audio amplifier, ideal for use in automotive emergency call (eCall), telematics, instrument cluster, and infotainment applications. The device provides up to 22 W into 4 Ω at less than 10% THD+N from a 14.4-V DC automotive battery. The wide operating voltage range and excellent efficiency make the device ideal for start-stop support or running from a backup battery when required. The integrated load-dump protection reduces external voltage clamp cost and size, and the onboard load diagnostics report the status of the speaker through I²C.

Figure 5. Typical Application Diagram

Figure 6. TAS5421-Q1 Functional Block Diagram
3.1.3 Automotive 60-V, 5-µA $I_{Q}$, 100-mA LDO Voltage Regulator With Enable and Power Good

The TPS7A16xx-Q1 ultra-low-power, low-dropout (LDO) voltage regulators offer the benefits of ultra-low quiescent current, high input voltage, and miniaturized high-thermal-performance packaging.

The TPS7A16xx-Q1 devices are designed for continuous or sporadic (power backup) battery-powered applications where ultralow quiescent current is critical to extending system battery life.

The TPS7A16xx-Q1 devices offer an enable pin (EN) compatible with standard CMOS logic and an integrated open-drain active-high power-good output (PG) with a user-programmable delay. These pins are intended for use in microcontroller-based, battery-powered applications where power-rail sequencing is required.

In addition, the TPS7A16xx-Q1 devices are ideal for generating a low-voltage supply from multicell solutions ranging from high-cell-count power-tool packs to automotive applications; not only can these devices supply a well-regulated voltage rail, but they can also withstand and maintain regulation during voltage transients. These features translate to simpler and more cost-effective, electrical surge-protection circuitry.

![Figure 7. Typical Application Diagram](image-url)
3.1.4 MSP430F2232 16-Bit Ultra-Low-Power MCU—8-KB Flash, 512B of RAM

The Texas Instruments MSP430™ family of ultra-low-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows the device to wake up from low-power modes to active mode in less than 1 µs.

Typical applications include sensor systems that capture analog signals, convert them to digital values, and then process the data for display or for transmission to a host system. Stand-alone radio-frequency (RF) sensor front ends are another area of application.
The TRS3223 consists of two line drivers, two line receivers, and a dual charge-pump circuit with ±15-kV electrostatic discharge (ESD) protection pin to pin (serial-port connection pins, including GND). The device meets the requirements of TIA/EIA-232-F and provides the electrical interface between an asynchronous communication controller and the serial-port connector. The charge pump and four small external capacitors allow operation from a single 3- to 5.5-V supply. The device operates at data signaling rates up to 250 kbit/s and a maximum of 30-V/μs driver output slew rate.

Flexible control options for power management are available when the serial port is inactive. The auto-powerdown feature functions when FORCEON is low and FORCEOFF is high. During this mode of operation, if the device does not sense a valid RS-232 signal, the driver outputs are disabled. If FORCEOFF is set low and EN is high, both drivers and receivers are shut off, and the supply current is reduced to 1 μA. Disconnecting the serial port or turning off the peripheral drivers causes auto-powerdown to occur. Auto-powerdown can be disabled when FORCEON and FORCEOFF are high. With auto-powerdown enabled, the device is activated automatically when a valid signal is applied to any receiver input. The INVALID output is used to notify the user if an RS-232 signal is present at any receiver input. INVALID is high (valid data) if any receiver input voltage is greater than 2.7 V or less than –2.7 V, or has been between –0.3 V and 0.3 V for less than 30 μs. INVALID is low (invalid data) if the receiver input voltage is between –0.3 V and 0.3 V for more than 30 μs.

![Figure 10. Logic Diagram](image-url)
A. C3 can be connected to VCC or GND.
B. Resistor values shown are nominal.
C. Nonpolarized ceramic capacitors are acceptable. If polarized tantalum or electrolytic capacitors are used, they should be connected as shown.

<table>
<thead>
<tr>
<th>VCC</th>
<th>C1</th>
<th>C2, C3, C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3 V ± 0.3 V</td>
<td>0.1 µF</td>
<td>0.1 µF</td>
</tr>
<tr>
<td>5 V ± 0.5 V</td>
<td>0.047 µF</td>
<td>0.33 µF</td>
</tr>
<tr>
<td>3 V to 5.5 V</td>
<td>0.1 µF</td>
<td>0.47 µF</td>
</tr>
</tbody>
</table>

Figure 11. Application Information
4 System Design Theory

The TIDA-00159 is designed to have the capability to enable phone calls to an emergency service center in the case of an accident. Figure 12 shows the eCall reference circuit board design.

![Figure 12. eCall Reference Circuit Board Design](image)

4.1 Input Or-ing and Backup Battery

Figure 13 shows the or-ing input and backup battery schematic.

![Figure 13. Or-ing Input and Backup Battery Schematic](image)
BH1 is a single-cell rechargeable lithium iron phosphate (LiFePO4) battery used to back up the system in the case of power failure of the car battery and has been selected because of its high, continuous-discharge capability of 21 A. The TPS7A1601 is a low-power, low-quiescent current, and LDO voltage regulator that is designed for battery powered applications such as this eCall system. The TPS7A1601 is used for the backup cell charging. The TPS7A1601, in combination with the logic circuitry, has OFF-battery capability as a safety measure in the case of a fault condition in the power path.

The TPS7A1601 is powered from the 5-V VCC rail generated by the TPS4333Q1. The TPS7A1601 provides an output charge at 3.6 V for the LiFePO4 cell. A trickle charge method has been implemented for the backup cell with the ability to switch the LDO supplying the charge voltage ON and OFF. The enable pin of the TPS7A1601 is connected to GPIO P3.0 of the MSP430 MCU. The purpose of this connection is to enable the LDO when the system input level reaches the boost enable threshold. The LDO is disabled when the system input level falls below the boost enable threshold, even when the system input is the LiFePO4 cell.

The series switch between the backup LiFePO4 cell and the series protection diode functions as a power OFF switch controlled by the MSP430 MCU when the system is powered from the backup LiFePO4 cell. The MSP430 MCU switches the LiFePO4 cell ON when the system input level reaches the boost enable threshold. The LiFePO4 cell then provides power to the system in the event that the car battery connection becomes severed. When the cell voltage falls below the “dead” threshold of 2.65 V, then the LiFePO4 cell is switched OFF.

NOTE: The boost output controller described in the following Section 4.2 must be enabled when the car battery connection has been severed for the backup cell battery to be able to simultaneously provide power to the system.

A series diode on the backup cell battery input has been included for protection against the automotive battery voltage.

4.2 PMIC Section

The TPS43330-Q1 PMIC is the primary, power conversion integrated circuit (IC) in the system. The device provides 10-V, 3.6-V, and 5-V outputs from the system input voltage of 4.5 V to 40 V. Figure 14 shows the design parameters used in the TPS43330-Q1 PMIC design spreadsheet.

![Figure 14. TPS43330-Q1 Schematic](image-url)
Table 2 shows the PMIC power supply design spreadsheet parameters.

### Table 2. PMIC Power Supply Design Spreadsheet Parameters

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>COMMENT</th>
<th>MIN</th>
<th>VALUE</th>
<th>MAX</th>
<th>UNIT</th>
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<tr>
<td>Output</td>
<td>Boost</td>
<td></td>
<td>10</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Buck A</td>
<td></td>
<td>3.6</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Buck B</td>
<td></td>
<td>5</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Input</td>
<td></td>
<td>4.5</td>
<td>12</td>
<td>40</td>
<td>V</td>
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<tr>
<td>Load current</td>
<td>Boost Load Current</td>
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<td></td>
<td>2500</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td>Boost A Load Current</td>
<td></td>
<td></td>
<td>100</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td>Buck B Load Current</td>
<td></td>
<td></td>
<td>600</td>
<td>mA</td>
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<td>Load step tolerance</td>
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<td></td>
<td>+364</td>
<td>mV</td>
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<td></td>
<td>Buck A</td>
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<td></td>
<td>75</td>
<td>mV</td>
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<tr>
<td></td>
<td>Buck B</td>
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<td>kHz</td>
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<tr>
<td>Switching frequency</td>
<td>Boost</td>
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<td>200</td>
<td></td>
<td>kHz</td>
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<tr>
<td></td>
<td>Buck A</td>
<td></td>
<td>400</td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td></td>
<td>Buck B</td>
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<td></td>
<td>kHz</td>
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<tr>
<td>Inductor</td>
<td>Selected Value for Boost</td>
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</tr>
<tr>
<td></td>
<td>Selected Value for Buck A</td>
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<td>47</td>
<td></td>
<td>µH</td>
</tr>
<tr>
<td></td>
<td>Selected Value for Buck B</td>
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<td>6.8</td>
<td></td>
<td>µH</td>
</tr>
</tbody>
</table>

### 4.2.1 Inductor Selection

The following subsections assume that the input voltage is 12 V and that the output voltage for the Boost, Buck A, and Buck B is 10 V, 3.6 V, and 5 V, respectively.

Figure 15 shows the boost output.
Figure 16 shows the boost controller output A.

Figure 17 shows the buck controller output B.
4.2.1.1 **Boost Inductor**

The maximum input current flows at the minimum input voltage and maximum load. The TAS5421 device that Section 4.3 details requires to run a 2-Ω speaker at 10 W. The amplifier load current is approximately 2.3 A and the Sierra Wireless Modem uses approximately 2.0 A. Assume the boost converter has an efficiency of 85% when $V_{\text{BAT}} = 12$ V and the load is 5 A, which is based on the graphs in the Typical Characteristics section of the TPS43330-Q1 data sheet [1]; see Equation 1:

$$P_{\text{IN (max)}} = \frac{P_{\text{OUT}}}{\text{Efficiency}} = \frac{60 \text{ W}}{0.85} = 70.58 \text{ W}$$

$$I_{\text{IN (max)}} (\text{at } V_{\text{BAT}} = 12 \text{ V}) = \frac{70.58 \text{ W}}{12 \text{ V}} = 5.88 \text{ A}$$

$$L = \frac{V_{\text{BAT}} \times t_{\text{ON}}}{I_{\text{IN, RIPPLEMAX}} \times 2 \times f_{\text{SW}}} = \frac{12 \text{ V}}{5.88 \text{ A} \times 2 \times 200 \text{ kHz}} = 5.1 \mu\text{H}$$

Designing for the discontinuous mode demands an even lower inductor value that does not saturate with high ripple currents. The boost circuit has been designed to ensure that the regulator never enters the continuous-conduction mode; otherwise, the circuit can become unstable.

Select a lower inductor value of 4 µH to ensure a high RHP-zero frequency while making a compromise that expects a high current ripple. This inductor selection also makes the boost converter operate in discontinuous conduction mode, where compensation is easier. The inductor saturation current must be higher than the peak inductor current and some percentage higher than the maximum current-limit value set by the external resistive sensing element.

4.2.1.2 **Buck A and Buck B Inductors**

Based on the typical characteristics for the $V_{\text{SENSE}}$ limit with a $V_{\text{IN}}$ versus duty cycle, the sense limit is approximately 65 mV ($V_{\text{IN}} / V_{\text{OUT}} = \text{duty cycle} \rightarrow 3.6 \text{ V} / 12 \text{ V} = 0.3$). Allowing for tolerances and ripple currents, select a $V_{\text{SENSE}}$ maximum of 10 mV (see Equation 2).

$$R_{\text{SENSE, A}} = \frac{10 \text{ mV}}{100 \text{ mA}} = 100 \text{ m\Omega}$$

For the optimal slope compensation and loop response, choose the inductor as such in Equation 3:

$$L_A = K_{\text{FLR}} \times R_{\text{SENSE}} \times f_{\text{SW}} = 200 \times \frac{100 \text{ m\Omega}}{400 \text{ kHz}} = 50 \mu\text{H}$$

The standard value of 47 µH has been selected. For the buck converter, select the inductor saturation currents and core to sustain the maximum currents.

For the second buck controller, the duty cycle is calculated to be 0.42 ($V_{\text{OUT}} / V_{\text{IN}} = \text{duty cycle} \rightarrow 5 \text{ V} / 12 \text{ V} = 0.42$). Allowing for tolerances and ripple currents, select a $V_{\text{SENSE}}$ maximum of 10 mV (see Equation 4).

$$R_{\text{SENSE, B}} = \frac{10 \text{ mV}}{600 \text{ mA}} = 16.7 \text{ m\Omega}$$

The chosen standard value is then selected to be 15 mΩ (see Equation 5):

$$L_B = K_{\text{FLR}} \times R_{\text{SENSE}} \times f_{\text{SW}} = 200 \times \frac{15 \text{ m\Omega}}{400 \text{ kHz}} = 7.5 \mu\text{H}$$

The standard value of 6.8 µH has been selected.
### 4.2.2 Output Capacitor Selection

As the preceding Figure 15, Figure 16, and Figure 17 show, the output capacitance was calculated to be 2×470-µF tantalum with 4×10-µF ceramics on the output of the boost, 23 µF for the Buck Output A and 48 µF for Buck Output B. The following subsections outline those calculations.

#### 4.2.2.1 Boost Output Capacitor

Recall in Section 4.2.1.1 that $I_{\text{IN(max)}} = 5.88$ A and $V_{\text{BAT(min)}} = 4.5$ V. To calculate the output capacitor first requires calculating the $f_{\text{RHP}}$ (right half-plane) zero (see Equation 6).

$$f_{\text{RHP}} = \frac{V_{\text{BAT(min)}}}{2\pi \times I_{\text{IN(max)}} \times L} = \frac{4.5}{2\pi \times 5.88 \times 2.7 \, \mu\text{H}} = 45.11 \, \text{kHz}$$

(6)

To ensure stability, select the output capacitor, $C_{\text{OUT}}$, such that $f_{\text{LC}} \leq f_{\text{RHP}} / 10$ calculates as shown in the following Equation 7:

$$\frac{1}{2\pi \times \sqrt{L \times C_{\text{OUT}}}} \leq \frac{f_{\text{RHP}}}{10}$$

$$C_{\text{OUT}} \geq \frac{1}{L \times \left(\frac{10}{f_{\text{RHP}} \times 2\pi}\right)^2}$$

(7)

Using only 460 µF of capacitance makes the relationship between $f_{\text{LC}}$ and $f_{\text{RHP}}$ only 4.52 kHz ≤ 41.5 kHz / 10. Choosing 2×470-µF decreases the $f_{\text{LC}}$ and allows for less output ripple (see Equation 8).

$$f_{\text{LC}} = \frac{1}{2\pi \times \sqrt{L \times C_{\text{OUT}}}} = 3.1 \, \text{kHz}$$

(8)

Because 3.1 kHz ≤ 41.5 kHz / 10, this satisfies the relationship between $f_{\text{LC}}$ and $f_{\text{RHP}}$. Also note the calculation in the following Equation 9

$$f_{\text{ESR}} = \frac{1}{2\pi \times C_{\text{OUT}} \times R_{\text{ESR}}} = \frac{1}{2\pi \times 980 \, \mu\text{F} \times 40 \, \text{m\Omega}} = 4.1 \, \text{kHz}$$

$$f_{\text{LC}} < f_{\text{ESR}} < f_{\text{C}} < f_{\text{RHP}}$$

(9)

Note that it is good engineering practice to use ceramic capacitors in conjunction with aluminum electrolytic capacitors so that the effective equivalent series resistance (ESR) decreases. In this design, four 10-µF capacitors were used in parallel with the 2×470-µF capacitors.

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**NOTE:** For further details on output capacitor impedance characteristics, see the section titled Output Capacitors Effect Feedback in the Input and Output Capacitor Selection application report [7].
4.2.2.2 Buck A and Buck B Output Capacitors

To determine the capacitance required for Buck A and Buck B, the combination of $V_{\text{OUTA (Ripple)}}$ and $\Delta V_{\text{OUTA}}$ must be within the limits set by the power-good comparator (PGTH is 7%). Estimate $\Delta V_{\text{OUTA}}$ to be approximately 50 mV so that it meets the PGTH requirement (see Equation 10).

$$C_{\text{OUTA}} \approx \frac{2 \times \Delta I_{\text{OUTA}}}{f_{\text{SW}} \times \Delta V_{\text{OUTA}}} = \frac{2 \times 95 \text{ mA}}{400 \text{ kHz} \times 50 \text{ mV}} = 9.5 \mu\text{F}$$

(10)

To allow for larger compensation components, a higher 22-µF value capacitor has been selected. For $C_{\text{OUTB}}$ choose $\Delta V_{\text{OUTB}} = 100$ mV (see Equation 11).

$$C_{\text{OUTA}} \approx \frac{2 \times \Delta I_{\text{OUTA}}}{f_{\text{SW}} \times \Delta V_{\text{OUTA}}} = \frac{2 \times 550 \text{ mA}}{400 \text{ kHz} \times 100 \text{ mV}} = 27.5 \mu\text{F}$$

(11)

A standard 47-µF value capacitor has been selected. An extra 1-µF ceramic capacitor for both Buck A and Buck B was used in parallel to mitigate higher frequencies.

4.2.3 Compensation Calculations

The following Figure 18 shows the compensation network for the TIDA-00159 TI Design.

![Figure 18. Compensation Network for TIDA-00159](image-url)
4.2.3.1 Boost Compensation

This subsection calculates the compensation for the boost circuit. The following Figure 19 is the error amplifier, which shows the use of Type-II compensation.

![Figure 19. Compensation and Error Amplifier Network for TPS43330-Q1 Boost](image)

In the following Equation 12, Equation 13, and Equation 14, the $V_{OUT} = 10 \text{ V}$, $C_{OUTA} = 980 \mu\text{F}$, $f_{ESR} = 6.5 \text{ kHz}$, so assume $f_c = 6 \text{ kHz}$ and $G = 8.2$.

$$R_3 = \frac{10^{G/20}}{8.5 \times 10^{-6} \text{ A} / V^2 \times V_{OUT}} = \frac{10^{0.2/20}}{85 \times 10^{-6} \text{ A} / V^2 \times 10 \text{ V}} = 3.0 \text{ k\Omega}$$  \hspace{1cm} (12)

Choose $R_3 = 2 \text{ k\Omega}$.

$$C_1 = \frac{10}{2\pi \times f_c \times R_3} = \frac{10}{2\pi \times 6 \text{ kHz} \times 2.0 \text{ k\Omega}} = 130 \text{ nF}$$  \hspace{1cm} (13)

Choose $C_1 = 220 \text{ nF}$ (0.22 \mu F).

$$C_2 = \frac{C_1}{2\pi \times R_3 \times C_1 \left(\frac{f_{SW}}{2}\right) - 1} = \frac{200 \text{ nF}}{2\pi \times 2 \text{ k\Omega} \times 220 \text{ nF} \left(\frac{200 \text{ kHz}}{2}\right) - 1} = 797 \text{ pF}$$  \hspace{1cm} (14)

Choose $C_2 = 820 \text{ pF}$.

**NOTE:** When solving for $C_1$, the closer standard value was 220 nF, so $R_3$ was back calculated to select a value in between $R_3$ and that which allows $C_1$ to be closer to 220 nF.
**4.2.3.2 Buck A and Buck B Compensation**

This section calculates the compensation for the Buck A and Buck B circuits. The following Figure 20 is the error amplifier, which shows the use of Type-II compensation.

![Figure 20. Compensation and Error Amplifier Network Used for Buck Controller Stability](image)

In the following Equation 15, Equation 16, and Equation 17, the values for Buck A are as follows: $V_{\text{OUT}} = 3.6 \text{ V}$, $C_{\text{OUT}} = 23 \text{ µF}$, $G_{\text{mBUCK}} = 1 \text{ ms}$, $V_{\text{REF}} = 0.8 \text{ V}$, and $K_{\text{CFB}} = 0.125 / R_{\text{SENSE}} = 1.25$.

$$R_3 = \frac{2\pi \times f_C \times V_{\text{OUT}} \times C_{\text{OUT}}}{G_{\text{mBUCK}} \times K_{\text{CFB}} \times V_{\text{REF}}} = \frac{2\pi \times 50 \text{ kHz} \times 3.6 \text{ V} \times 23 \text{ µF}}{1 \text{ ms} \times 1.25 \times 0.8 \text{ V}} = 26 \text{ kΩ}$$

(15)

Choose $R_3 = 27.4 \text{ kΩ}$.

$$C_1 = \frac{10}{2\pi \times f_C \times R_3} = \frac{10}{2\pi \times 50 \text{ kHz} \times 24.9 \text{ kΩ}} = 1.3 \text{ nF}$$

(16)

Choose $C_1 = 1 \text{ nF}$ (1000 pF).

$$C_2 = \frac{1 \text{ nF}}{2\pi \times R_3 \times C_1 \left(\frac{f_{\text{SW}}}{2}\right)} = \frac{1 \text{ nF}}{2\pi \times 24.9 \text{ kΩ} \times 1 \text{ nF} \left(\frac{400 \text{ kHz}}{2}\right)} = 33 \text{ pF}$$

(17)

Choose $C_2 = 30 \text{ pF}$.

In the following Equation 18, Equation 19, and Equation 20, the values for Buck B are as follows: $V_{\text{OUT}} = 5 \text{ V}$, $C_{\text{OUT}} = 48 \text{ µF}$, $G_{\text{mBUCK}} = 1 \text{ ms}$, $V_{\text{REF}} = 0.8 \text{ V}$, and $K_{\text{CFB}} = 0.125 / R_{\text{SENSE}} = 8.33$.

$$R_3 = \frac{2\pi \times f_C \times V_{\text{OUT}} \times C_{\text{OUT}}}{G_{\text{mBUCK}} \times K_{\text{CFB}} \times V_{\text{REF}}} = \frac{2\pi \times 50 \text{ kHz} \times 5 \text{ V} \times 48 \text{ µF}}{1 \text{ ms} \times 8.33 \times 0.8 \text{ V}} = 11.3 \text{ kΩ}$$

(18)

Choose $R_3 = 12k \text{ Ω}$.

$$C_1 = \frac{10}{2\pi \times f_C \times R_3} = \frac{10}{2\pi \times 50 \text{ kHz} \times 12 \text{ kΩ}} = 2.65 \text{ nF}$$

(19)

Choose $C_1 = 2.2 \text{ nF}$ (2200 pF).

$$C_2 = \frac{2.2 \text{ nF}}{2\pi \times R_3 \times C_1 \left(\frac{f_{\text{SW}}}{2}\right)} = \frac{2.2 \text{ nF}}{2\pi \times 12 \text{ kΩ} \times 2.2 \text{ nF} \left(\frac{400 \text{ kHz}}{2}\right)} = 68.4 \text{ pF}$$

(20)

Choose $C_2 = 68 \text{ pF}$.

**NOTE:** calculating compensation often requires some trial and error to find the right balance of values required to stabilize the controller.
4.3 TAS5421 Class-D Audio Amplifier

The TAS5421-Q1 is a mono digital audio amplifier that has been specifically designed for automotive infotainment systems such as telematics, cluster, and eCall (see Figure 21). An audio signal modulates the PWM output in a Class D amplifier, which results in a combination of the audio band plus the switching frequency at the amplifier output. To filter the PWM switching frequency, a low-pass filter with a cutoff frequency lower than the switching frequency is applied in the output.

BD modulation is a switching technique that modulates the duty cycle of the difference of the output signals such that its average content corresponds to the input analog signal. The bridge-tied load (BTL) outputs are not inverse to each other. BD modulation has a significant source of common-mode content in its output (see Figure 22).

Figure 21. TAS5421 Schematic

Figure 22. LC Filter for BD Modulation With Balanced Two-Pole Filter
The balanced two-pole filter does not have a common-mode swing problem and is critically damped at $Q = \frac{1}{\sqrt{2}}$ (see Figure 23).

![Figure 23. Filter Damping (Q Factor)](image)

The values have been selected to be $R_{BTL} = 8 \, \Omega$, $f_o = 50 \, \text{kHz}$, and $Q = \frac{1}{\sqrt{2}}$ (see Equation 21).

$$L_{BTL} = \frac{R_{BTL}}{Q \times 2 \times \omega_o} = \frac{8}{\frac{1}{\sqrt{2}} \times 2 \times 2 \pi \times 50 \, \text{kHz}} = 18 \, \mu\text{H}$$

(21)

The $L_{BTL} = 10-\mu\text{H}$ 7G08B-100M-R coupled inductor has ultimately been chosen because this package was half the size of two inductors, which significantly reduces the required footprint (see Equation 22).

$$C_g = \frac{2 \times Q}{R_{BTL} \times \omega_o} = \frac{2 \times \left(\frac{1}{\sqrt{2}}\right)}{8 \times 2 \pi \times 50 \, \text{kHz}} = 0.563 \, \mu\text{F}$$

(22)

A standard value of capacitance has been chosen at 0.68 $\mu$F.
4.4 RS-232 Interface

The RS-232 transceiver is the TRS3223-Q1 device, which operates with a 3.3-V power supply (see Figure 24). J2 is a 15-pin D-sub connector. This interface is used to connect the Sierra Wireless Modem. The software for the MSP430 MCU features AT commands that implement through this connection.

Figure 24. RS-232 Transceiver
5 Getting Started Hardware and Software

The following subsections assume that the user has installed the TI Code Composer Studio™ (CCS) software and the drivers for the MSP MCU Programmer and Debugger (MSP-FET). The drivers must be built before the starting the procedure outlined in Section 5.2.

5.1 Hardware Setup

Figure 25 shows the TIDA-00159 hardware setup. Implement the following steps to test the TIDA-00159 reference design:

1. Connect the positive and negative wires of the 8-Ω speaker to the terminals of the J5 connector.
2. Insert the LiFePO4 backup battery into the battery holder.
3. Sierra Wireless Modem:
   (a) Connect the 5-V board power to the Sierra Wireless Modem.
   (b) Connect the sierra wireless modem to the TIDA-00159 design through the D-sub connector.
4. MSP430:
   (a) Connect the MSP-FET programmer to the JTAG connector.
   (b) Plug in the USB to a computer.
5. Connect the optimal 12-V DC power to J1.

![Figure 25. Hardware Connection Setup](image-url)
5.2 Software Setup

5.2.1 Application Information

The main function of the software is to configure the communication between the Sierra Wireless Modem to make an emergency call regardless of whether the design is running from the main battery (12-V input) or the LiFePO4 backup battery. The following Figure 26 is a flow chart that shows the main.c functions.

![Figure 26. Main.c Flow Chart](image)

First, the program initiates the ADC, timer, and GPIOs. The program then establishes communication to the modem. After initialization, an eCall is ready to be placed. The following flow chart in Figure 27 shows the functions in eCall.c.
To place an eCall, the TAS5421 diagnostics are read in the function i2c_TAS5421_Load_Diagnostics() to check whether any faults exist. If no faults exist, the ready-to-send (RTS) indicator is set and the “eCall” entry, which has been programmed in the SIM phonebook, is subsequently called. The orange light-emitting diode (LED) turns ON at this point and a response is retrieved from the modem through the get_AT_Response(). In the get_AT_Response(), the orange, yellow, and red LEDs are used to indicate the corresponding responses, as Table 3 shows:

<table>
<thead>
<tr>
<th>RESPONSE DETECTED</th>
<th>LED</th>
<th>DURATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call successful</td>
<td>Orange LED</td>
<td>1 time</td>
</tr>
<tr>
<td>Hang-up</td>
<td>Red LED</td>
<td>1 time</td>
</tr>
<tr>
<td>Busy</td>
<td>Yellow LED</td>
<td>2 times</td>
</tr>
<tr>
<td>No carrier</td>
<td>Red LED</td>
<td>2 times</td>
</tr>
<tr>
<td>No answer</td>
<td>Yellow LED</td>
<td>3 times</td>
</tr>
<tr>
<td>Error</td>
<td>Red LED</td>
<td>3 times</td>
</tr>
</tbody>
</table>

**Table 3. LED Responses**
In the event that the system-level input reaches the boost enable threshold, the following sequence of code is initiated, as the flow chart in Figure 28 shows:

When the input reaches the threshold for the boost controller, the boost is simultaneously enabled with the charge circuit. Subsequently, the battery is turned ON such that the battery can continue providing power to the rest of the system. Note that the boost controller must be enabled to allow the battery switch instantiation. When the system has been running long enough on the backup battery for the battery voltage to drop from 3.3 V to 2.85 V, the Low_Battery_Detect() function turns on the yellow light. Eventually, the voltage drops to 2.65 V and the system shuts down.

5.2.2 Configuring Application

1. Open the CCS software and import Automotive_eCall from http://www.ti.com/tool/TIDA-00159
2. Configure the application
3. Build the project:
   (a) In the interface, navigate to Project → Build Project
   (b) If using the default settings, this action generates the file Automotive_eCall.out
4. Next, debug the project:
   (a) In the interface, navigate to Run → Debug
5. Run the program:
   (a) In the interface, navigate to Run → Resume
6. Run the application
6 Testing and Results

The following tests evaluate the power rails for the TIDA-00159 reference design for the following cases:

- Start-up power sequence from a car battery connection
- Call from car battery connection
- Overvoltage protection
- Disconnecting a car battery connection
- Short-to-GND from backup cell battery
- Reconnecting a car battery connection

Unless otherwise noted, a Dell 19.5-V AC adapter power supply was used during testing as a substitute for a car battery. Figure 29 shows the block diagram and where the PMIC, 10-V, 5-V, and 3.6-V connections were measured. The colors in the block diagram correspond to the voltage rails in the oscilloscope shots that the following Section 6.1 through Section 6.7 show.

Figure 29. TIDA-00159 System Block Diagram
6.1 Start-up Power Sequence From Car Battery Connection

The following test report addresses the start-up sequence of the power rails after connecting the car battery. Figure 30 shows the start-up sequence after connecting the 19.5-V power supply.

Figure 30. Start-up From Car Battery

6.2 Call When Car Battery is Connected

The following test report addresses the power rails during a call with the car battery connected. Figure 31 shows the power rails during a call with the 19.5-V power supply connected.

Figure 31. Call off Car Battery
6.3 Overvoltage Protection

The following test report addresses the power rails after the overvoltage protection threshold for the car battery connection has been reached. A different power supply was used for the car battery connection in this test to exceed the 25.5-V threshold voltage.

Figure 32 shows the power rails before and after reaching the overvoltage protection threshold of 25.5 V.

\[\text{Figure 32. Overvoltage Protection}\]

6.4 Car Battery Disconnected

The following test shows the power rails after the car battery has been disconnected. Figure 33 shows the power rails after disconnecting from the 19.5-V power supply.

\[\text{Figure 33. Car Battery Disconnection}\]
6.5 Short-to-GND From Back-up Cell Battery

Figure 34 shows the power rails while the car battery connection was being shorted to GND.

![Figure 34. Short-to-GND From Back-up Battery](image)

6.6 Call From Back-up Cell Battery

Figure 35 shows the power rails during a call from the back-up cell battery with the car battery disconnected.

![Figure 35. Call From Back-Up Battery](image)
6.7 Car Battery Reconnected

Figure 36 shows the power rails after reconnecting the 19.5-V power supply.
7 Design Files

7.1 Schematics
To download the schematics, see the design files at: http://www.ti.com/tool/TIDA-00159.

7.2 Bill of Materials
To download the bill of materials (BOM), see the design files at http://www.ti.com/tool/TIDA-00159.

7.3 PCB Layout Recommendations
The TIDA-00159 PCB is a four-layer board comprising the following layers: a top layer that houses the majority of components, a second layer as GND, a third layer as PWR, and the bottom layer for signals. For a complete guide, follow the recommendations for individual components in the following subsections.

7.3.1 TPS43330-Q1 Layout
Carefully consider the layout recommendations in the Layout section of the TPS43330-Q1 data sheet when doing the layout [1].

7.3.1.1 Boost Layout
The path formed from the input capacitors (C11 and C12), inductor (L1), low-side switch (Q3), and current sense (R25) must have short leads and PC trace lengths. This specification similarly applies for the trace from the inductor to Schottky diode D5 to the output capacitors C13 and C14 (see Figure 37).

Figure 37. Boost Layout
Additionally, the overcurrent-sensing shunt resistor (R21) requires noise filtering and the filter capacitor (C19) is placed close to pin 2 (see Figure 38).

![Figure 38. Boost Layout 2](image)

7.3.1.2 Buck A and Buck B Layout

The $V_{\text{IN}}$ is routed on layer 1 with $V_{\text{OUTB}}$ 5 V and $V_{\text{OUTA}}$ 3.3 V routed on PWR layer 3.

As Figure 39 shows, the drains of the high-side field-effect transistors (FETs), Q2 and Q5, are connected close to the positive terminal of input capacitor (C14).

![Figure 39. Buck A and Buck B Layout](image)
Figure 40 shows the decoupling capacitor C26 connected between the drain of Q2 and the source of Q4 for Buck B. The same configuration is used for Buck A with C20, Q5, and Q6.

The Kelvin-current sensing for the shunt resistor (R31 and R20) has traces with minimum spacing and are routed in parallel with each other (see Figure 41).
The resistor divider for sensing the output voltage connects between the positive terminal of its respective output capacitor and \( C_{OUTA} \) or \( C_{OUTB} \) and the IC signal ground. Carefully ensure that these components and their traces are nowhere near the switching nodes or high-current traces (see Figure 42).

![Figure 42. Buck B Feedback Resistors](image)

### 7.3.2 TAS5421 Layout

For the TAS5421 layout, the recommendations listed in the TAS5421 data sheet were carefully considered [2]. The major considerations surround the thermal dissipation and electromagnetic compatibility (EMC) performance. As the data sheet recommends, the top, GND, PWR, and signal layers have been designed to optimize the performance of the TAS5421 device.

On the top layer, the GND planes are located where the TAS5421 has been soldered directly to the thermal pad and has an optimal number of vias to allow for dissipation to the GND plane below (see Figure 43). Additionally, a short distance was maintained between the output LC filter to suppress the opportunity for EMC radiation. The output capacitors were placed on a common ground to help with common-mode noise.

![Figure 43. TAS5421 Layout Layer 1](image)
As previously mentioned, on the second layer, the GND plane is accessed through vias for improved thermal performance (see Figure 44).

Figure 44. TAS5421 Layout Layer 2

On the third layer, the PWR plane is routed specifically to provide a short distance to the inputs of the TAS5421 device (see Figure 45).

Figure 45. TAS5421 Layout Layer 3

Finally, on the bottom signal layer, the I²C (routed to TP14 and TP13, then routed on the top layer) and Audio_NFault lines are routed such that there is no interference with other GND or PWR planes (see Figure 46).

Figure 46. TAS5421 Layout Layer 4
7.3.3 **MSP430™ and TRS3223 Layouts**

Routing for the MSP430 MCU and TRS3223 device is mostly performed on the top layer and bottom signal layer (see Figure 47.).

![Figure 47. Top: MSP430™ and TRS3223 Layer 1 Bottom: MSP430™ and TRS3223 Bottom Layer](image)

7.3.4 **Layout Prints**

To download the layer plots, see the design files at [http://www.ti.com/tool/TIDA-00159](http://www.ti.com/tool/TIDA-00159).

7.4 **Altium Project**

To download the Altium project files, see the design files at [http://www.ti.com/tool/TIDA-00159](http://www.ti.com/tool/TIDA-00159).

7.5 **Gerber Files**

To download the Gerber files, see the design files at [http://www.ti.com/tool/TIDA-00159](http://www.ti.com/tool/TIDA-00159).

7.6 **Assembly Drawings**

To download the assembly drawings, see the design files at [http://www.ti.com/tool/TIDA-00159](http://www.ti.com/tool/TIDA-00159).

8 **Software Files**

To download the software files, see the design files at [http://www.ti.com/tool/TIDA-00159](http://www.ti.com/tool/TIDA-00159).
9 References

1. Texas Instruments, *TPS4333x-Q1 Low Iq Single Boost, Dual Synchronous Buck Controller*, TPS4333x-Q1 Data Sheet (*SLVSA82*)
2. Texas Instruments, *TAS5421-Q1 22-W Mono Automotive Digital-Audio Amplifier With Load Dump and I2C Diagnostics*, TAS5421-Q1 Data Sheet (*SLOS814*)
3. Texas Instruments, *TPS7A16xx-Q1 60-V, 5-μA IQ, 100-mA, Low-Dropout Voltage Regulator, TPS7A16xx-Q1*, TPS7A16xx-Q1 Data Sheet (*SBVS188*)
4. Texas Instruments, *MIXED SIGNAL MICROCONTROLLER*, MSP430F22x2 and MSP430F22x4 Data Sheet (*SLAS504*)
6. Texas Instruments, *3-V To 5.5-V MULTICHANNEL RS-232 LINE DRIVER/RECEIVER WITH ±15-kV ESD PROTECTION*, TRS3223-Q1 Data Sheet (*SLLS950*)

10 Acknowledgments

Thank you to Nikkan Yadegary for the schematics, board files, and coding required for this design.

11 About the Author

HOPE BOVENZI is a systems engineer at Texas Instruments. Hope earned her bachelor of science in electrical engineering from the University of California at Davis. At Texas Instruments, she is responsible for developing reference design solutions for the Automotive Infotainment and Cluster segment and has a background in power design.
# Revision History

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

<table>
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<tr>
<td>• Changed the landing page to updated features and resources and completed design from previous, three-page preview status</td>
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