TI Designs

Multiple-Channel Temperature Sensing for Automotive LED Headlights Reference Design

Overview

This TI Design details a solution on how to drive a string of LED headlights, measure the temperature of the LEDs, and implement support for thermal foldback, which reduces the current in the LEDs as the LED temperatures rise. The design uses TI Temperature sensing solutions instead of NTC thermistors. This TI Design should be interfaced with a microcontroller to do the thermal foldback current derating of the LEDs. The input stage of the design is EMI- and EMC-filtered and can be directly supplied by a car battery.

Resources

TIDA-01381	Design Folder
TPS92691-Q1	Product Folder
TMP423-Q1	Product Folder

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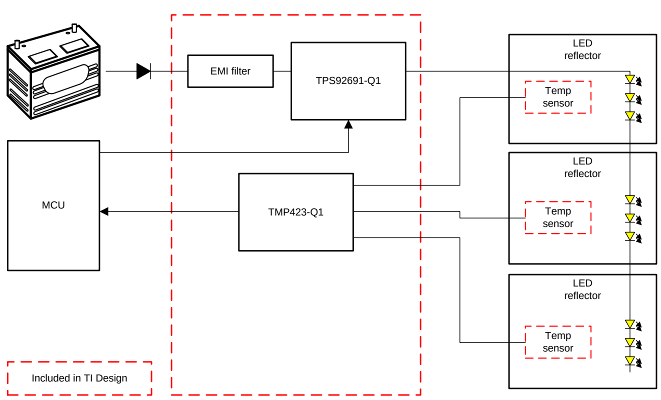
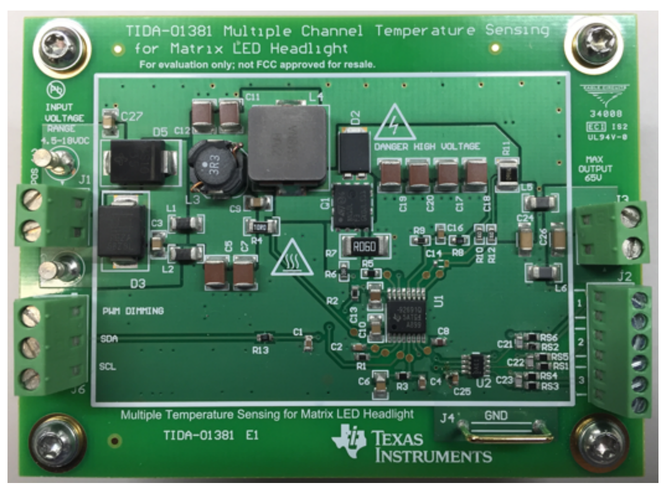
Features

- Multiple-Channel Temperature Sensing
- Efficiency-Optimized Design
- Operation Through Cold Crank
- Load Dump Tolerant
- Reverse Battery Protection
- Thermal Foldback

Applications

- Automotive Front Lighting
- Automotive Rear Lighting





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1 System Overview

1.1 System Description

This system is designed to drive a string of LEDs, measure their temperature remotely, and reduce the current through the LEDs accordingly. This TI Design includes key peripherals such as electromagnetic interference (EMI) and electromagnetic compatibility (EMC) filtering voltage-conditioning (shunt regulator), LED drive, and temperature sensing. Note that this TI Design was made with the automotive standards in mind, but it was not qualified.

The TIDA-01381 has been designed with the following points in consideration:

- Must be able to measure the temperature of the LEDs remotely
- Satisfy power requirements for one TPS92691 device driving a string of 1 to 12 LEDs for a headlight
- Operate over the full range of automotive battery conditions:
  – VIN(min) down to 5 V, simulating a cold-cranking condition (ISO 7637-2:2004 pulse 4)
  – VIN(max) up to 18 V, simulating the upper range of normal battery operation
- Survive and continue operation through:
  – Load dump (ISO 7637-2:2004 pulses 5a)
  – Double battery condition
- Output protected against shorts to battery and GND voltage
- Optimize the individual blocks for smallest power dissipation and highest efficiency
- Board layout must be set up in such a way to minimize the footprint of the solution while maintaining high performance
- Provide flexible board interface to either mate to custom board through screw terminals
- Accuracy in temperature measurements across the full temperature range
- Low power consumption of temperature sensing circuit across temperature

1.2 Key System Specifications

Table 1. Electrical Characteristics

PARAMETER		COMMENTS	MIN	TYP	MAX	UNIT
SYSTEM INPUT AND OUTPUT						
V_{IN}	Operating input voltage	Battery-voltage range; outputs are functional	5	14	18	V
V_{UVLO}	Input UVLO setting	Undervoltage lockout (UVLO)	—	4.5	—	—
V_{SWMax}	Vmax switch	Maximum switch node voltage	—	—	100	V
V_{OUT}	Output voltage	LED+ to LED– (Boost)	—	33	60	V
V_{TR}	Transient immunity	Load dump (ISO7637-2)	—	—	60	V
V_{IN_MIN}	Minimum input voltage	Cold crank (ISO 7637-2)	5	—	—	V
I_{IN}	Input current	Output at full load	—	2.52	—	A
I_{OUT}	Output current	Maximum current per string	62.5	1000	1138	mA
Maximum output power	—	—	—	—	33	W
$LED_{Open\ and\ short\ detect}$	LED open and short detection	—	—	Yes	—	—
$LED_{Single\ short\ detect}$	LED single-short detection	—	—	No	—	—
VCC	Power to TMP423-Q1		—	3.3	—	V
THERMAL						
T_A	Temperature range	Operating/ambient temperature	–40	—	125	C
PULSE TOLERANCE						
Cold crank	Operational					
Jump start	Operational					
BASEBOARD						
Number of layers	Two layers, single-side populated					
Form factor	64 mm × 45 mm (not including optional headers and mounting holes)					

1.3 Block Diagram

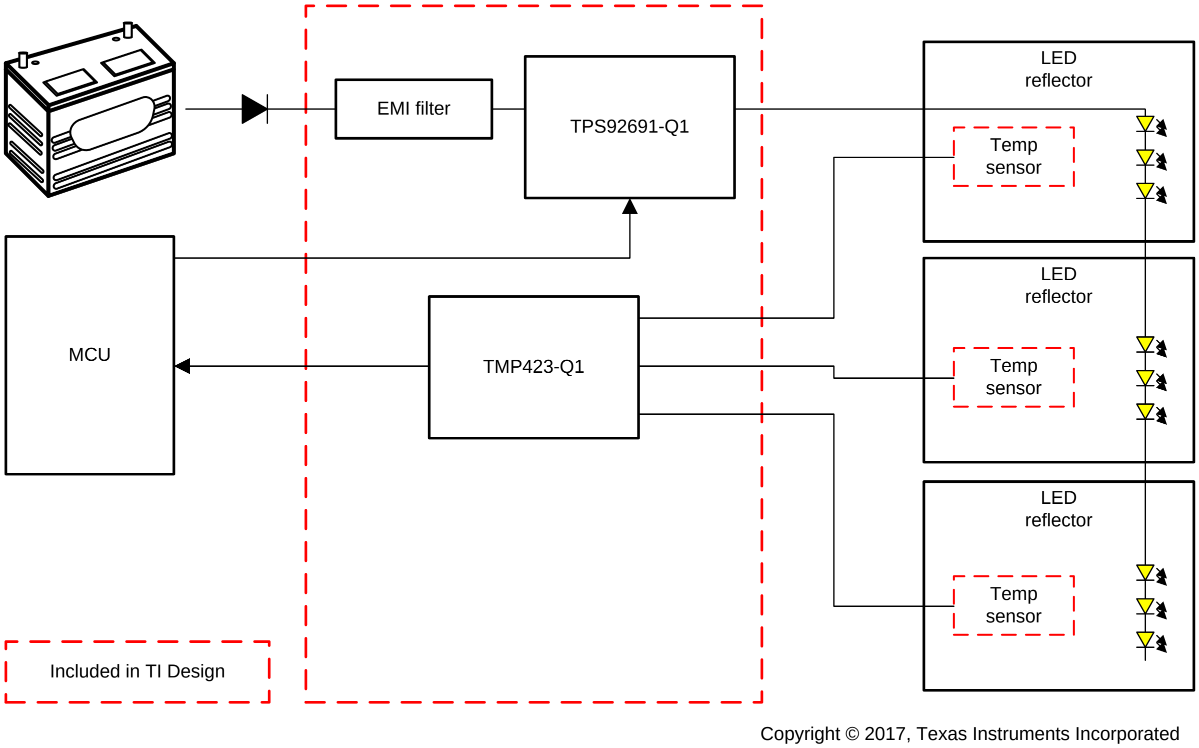

Figure 1. TIDA-01381 Block Diagram

1.4 Highlighted Products

1.4.1 TPS92691-Q1

The TPS92691-Q1 is a versatile LED controller that can support a range of step-up or step-down driver topologies (see Figure 2). The device implements a fixed-frequency, peak-current-mode control technique with programmable switching frequency, slope compensation, and soft-start timing. The device incorporates a high-voltage (65-V) rail-to-rail current sense amplifier that can directly measure LED current using either a high-side or a low-side series sense resistor. The amplifier is designed to achieve low-input offset voltage and attain better than ±3% LED current accuracy over a junction temperature range of 25°C to 140°C and output common-mode voltage range of 0 to 60 V.

LED current can be independently modulated using either analog or PWM dimming techniques. A linear analog dimming response with a 15:1 range is obtainable by varying the voltage from 140 mV to 2.25 V across the high-impedance analog adjust (IADJ) input. PWM dimming of LED current can be achieved by modulating the PWM input pin with the desired duty cycle and frequency. Use the DDRV gate driver output to enable series FET dimming functionality to obtain over a 1000:1 contrast ratio.

The TPS92691-Q1 supports continuous LED status check through the current monitor (IMON) output. This feature allows for LED short circuit or open circuit detection and protection. Additional fault protection features include VCC UVLO, output OVP, switch cycle-by-cycle current limit, and thermal protection.

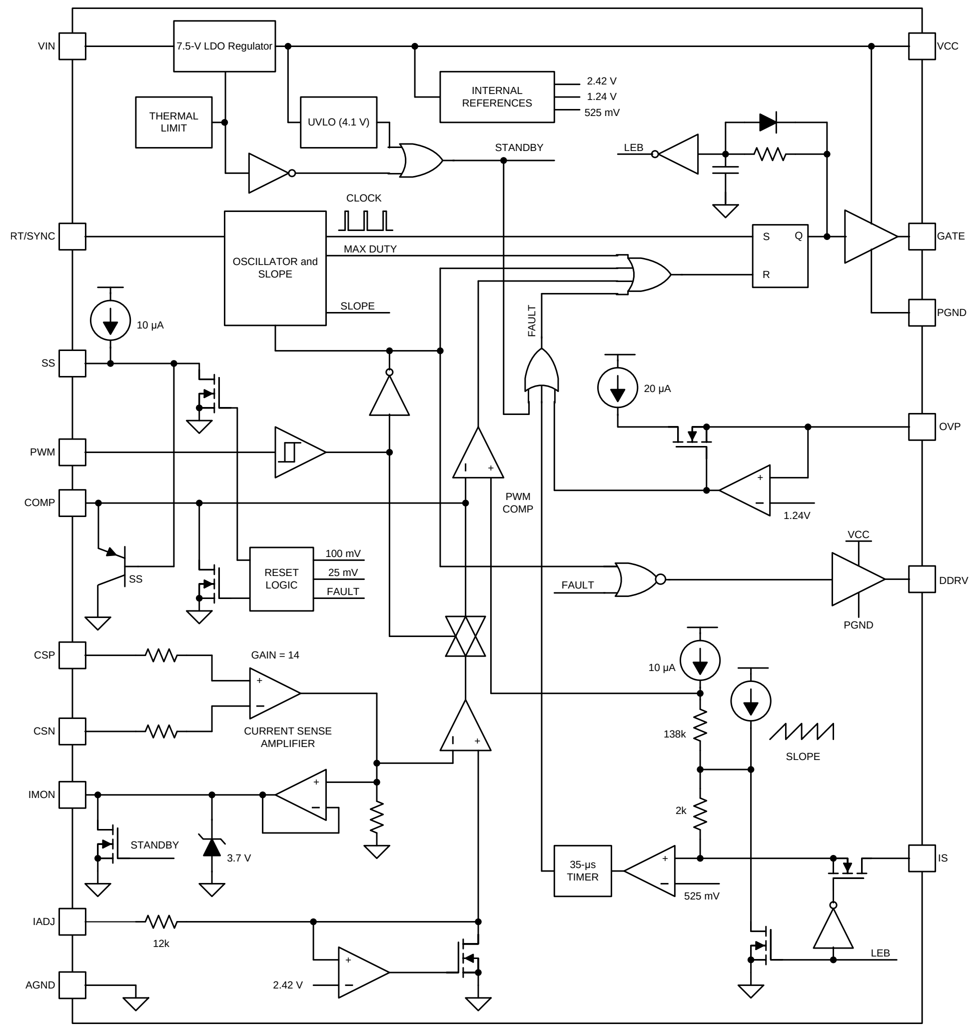

Figure 2. TPS92691-Q1 Functional Block Diagram

1.4.2 TMP423-Q1

The TMP423-Q1 is a remote temperature sensor monitor with a built-in local temperature sensor. The remote temperature sensor diode-connected transistors are typically low-cost, NPN- or PNP-type transistors or diodes that are an integral part of microcontrollers, microprocessors, or FPGAs. Remote accuracy is ±1°C for multiple IC manufacturers with no calibration needed. The two-wire serial interface accepts SMBus write byte, read byte, send byte, and receive byte commands to configure the device. The TMP423-Q1 includes series resistance cancellation, programmable non-ideality factor, wide remote temperature measurement range (up to 150°C), and diode fault detection.

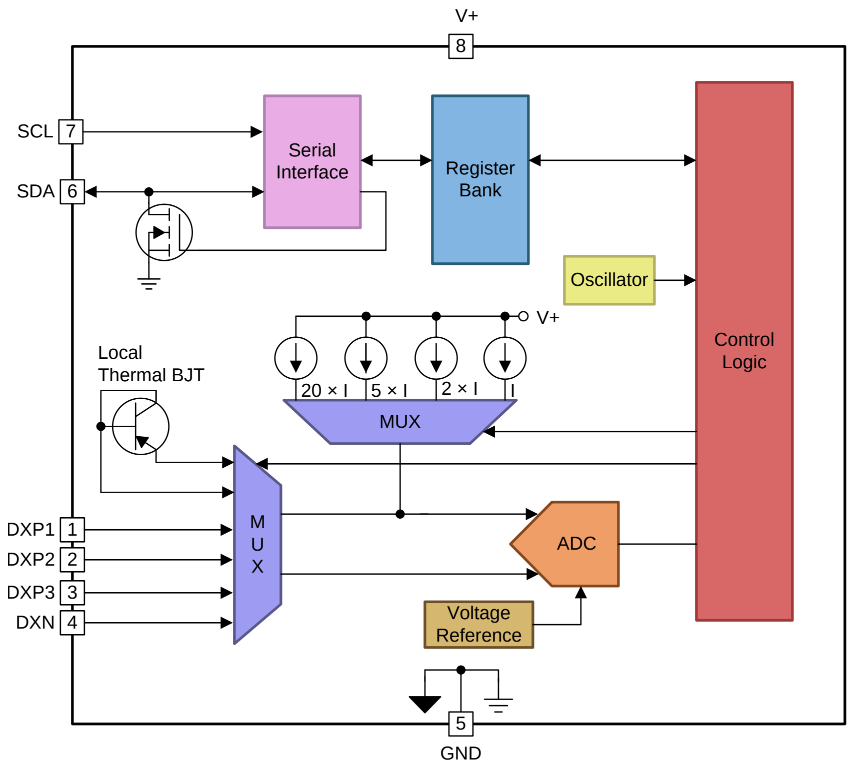

Figure 3. TMP423-Q1 Functional Block Diagram

2 System Design Theory

2.1 PCB and Form Factor

This TI Design is not intended to fit any particular form factor. The specific and primary objective of the design with regards to the PCB is to make a solution that is compact while still providing a way to test the performance of the board. Figure 4 shows a 3D rendering of the board.

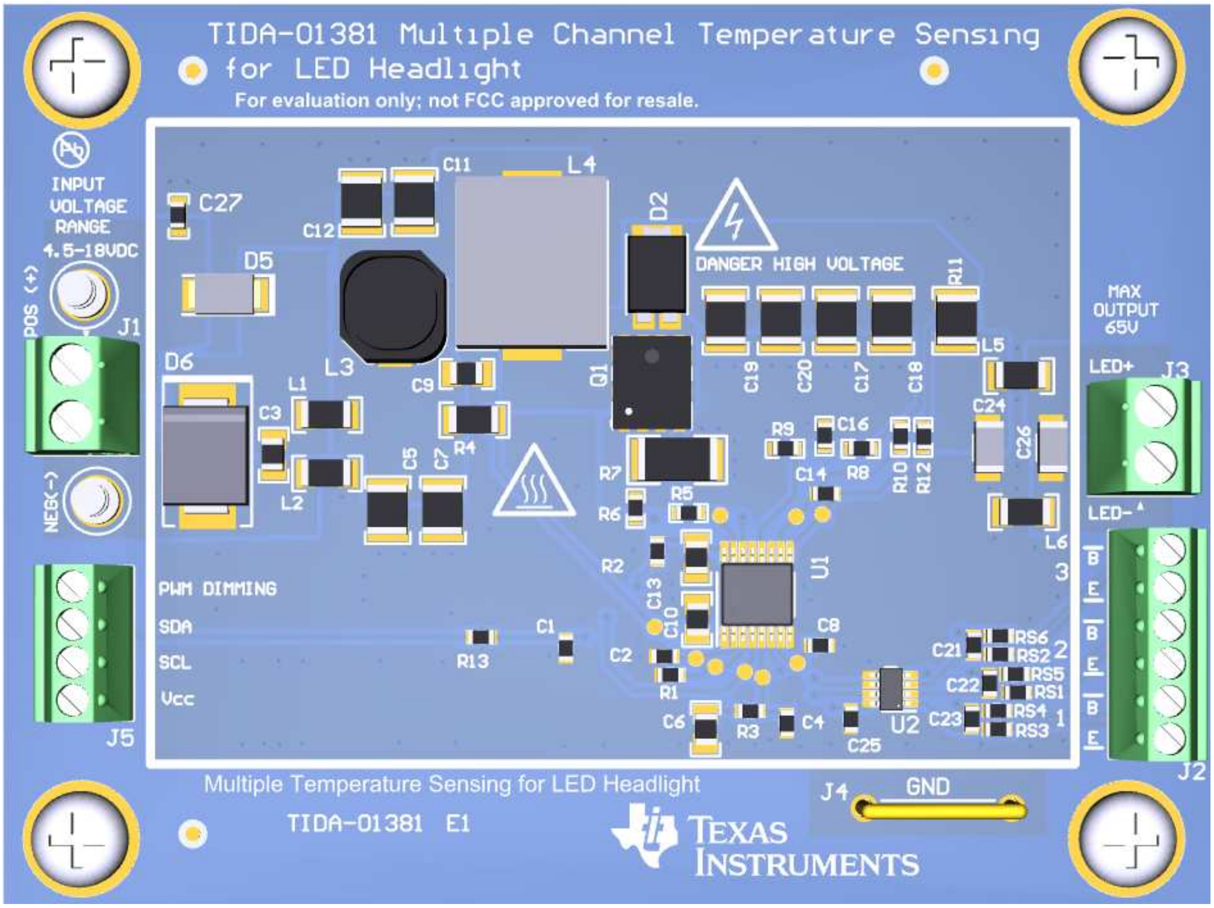

Figure 4. 3D Render of TIDA-01381 Board

In a final-production version of this TI Design, several techniques may be used to reduce the size of the solution:

- Test points, headers, sockets, standoffs, and banana plugs can be removed; these blocks can be removed because they do not service a direct function for the board
- The number, size, and value of capacitors in the system can be optimized
- The application may not require an input-conducted emissions EMI (PI) filter

2.2 Optimizing Board Performance Based on LED String Voltage and Current

The default board schematic has been configured to operate over a wide range of LED currents (62.5 mA to 1.138 A) and string configurations (1 to 20 LEDs). The driver operation, efficiency, and transient response can be improved by reconfiguring the schematic for a given LED current and LED string forward-voltage drop. The LED current sense resistor ($R_{CS} = R_{11}$) value can be calculated based on the maximum allowable differential voltage of 172 mV, which is achieved by pulling the IADJ pin to VCC through an external resistor. The slope compensation voltage can be adjusted by changing the switch current sense resistor, $R_{IS} = R_7$, based on the maximum expected LED stack voltage. The proportional integral compensation network can be tuned to achieve high bandwidth and desired phase margin for a specified range of input and output voltages. See the TPS92691-Q1 datasheet[2] for more details.

2.3 Switching Frequency

The switching frequency of the design is set for 390 kHz set by R1 and is below the AM band. The equation to choose R1 based on a switching frequency, f_{SW}(Hz) is shown in Equation 1.

$$R1 = 1.432 \times \frac{10^{10}}{\left(f_{SW}\right)^{1.047}} \tag{1}$$

2.4 PWM Dimming (IADJ)

The PWM dimming signal is connected to the IADJ pin of TPS92691-Q1 through a low-pass filter. The IADJ pin is what can be used to control the current through the LEDs, I_{LEDS}. The IADJ analog voltage forces a voltage across the sense resistor, $V_{(CSP\text{-}CSN)}$, which divided by the sense resistor, R_{26}, gives the current through the LEDs. Following the equations give the analog voltage needed to get a desired current.

$$I_{LEDs} = \frac{V_{(CSP-CSN)}}{R_{11}} \tag{2}$$

$$V_{(CSP-CSN)} = \frac{V_{IADJ}}{14} \tag{3}$$

$$I_{LEDs} = \frac{\left(\frac{V_{IADJ}}{14}\right)}{R_{26}} \tag{4}$$

The simplest way to have an adjustable analog input voltage, as required for the IADJ pin, is to feed a PWM signal from a microcontroller through a low-pass filter. The way to calculate what analog voltage will come out of a filtered PWM signal is in Equation 5, where V_{GPIO} is the voltage of microcontroller pin, normally 3.3 V or 5 V.

$$V_{IADJ} = \text{Duty cycle} \times V_{GPIO} \tag{5}$$

On the PWM dimming signal of J5, there is a low-pass RC filter of 2.2 kΩ and 0.1 µF, making the cutoff frequency 250 Hz. In testing, a 120-kHz PWM signal came into this pin from a microcontroller. This RC filter can be adjusted per PWM frequency chosen by changing R13 and C1.

2.5 Output Overvoltage Protection (OVP)

As automotive environments are harsh, good designs incorporate protection features against harsh electrical transient scenarios. This TI Design incorporates output overvoltage protection in the event of an output open circuit. This prevents damaging the output capacitors, the rectifier diode, the switching field-effect transistor (FET), the CSP pin, and the CSN pin of the device. Pins V_{IN}, V_{CSP} and V_{CSN} have a maximum voltage of 65 V, which means the OVP should be set so that the maximum output voltage does not reach 65 V. Also the resistors must be set to allow a hysteresis that will not go above that 65 V. The following equations show how to choose the values for the resistor divider going into the OVP pin.

$$R8 = \frac{V_{OV(HYS)}}{\left(20 \times 10^{-6}\right)} = \frac{10\ V}{\left(20 \times 10^{-6}\right)} = 500\ k\Omega \tag{6}$$

$$R9 = R8 \times \left(\frac{1.24}{\left(V_{O(OV)} - 1.24\right)}\right) = 500\ k\Omega \times \left(\frac{1.24}{(62 - 1.24)}\right) = 10\ k\Omega \tag{7}$$

2.6 Current Monitoring (IMON)

If current monitoring is desired, the IMON pin on the TPS92691-Q1 can be read by an ADC of the microcontroller and then the device can be shut off when a fault is detected. The IMON pin represents 14 times the voltage $V_{CSP\text{-}CSN}$. If the TPS92691-Q1 is not interfaced with a microcontroller for overcurrent protection, there is a discrete way to enable this feature. If current monitoring would rather be done discretely, see *TPS92691/-Q1 Multi-Topology LED Driver with Rail-to-Rail Current Sense Amplifier*.

2.7 Temperature Sensing Layout

In the TMP423-Q1 datasheet, there are guidelines of how to layout the device. With this TI Design, care was taken so that trace lengths of the DXN paths were kept to be as close to the same length as possible and used the same number of copper-to-solder connections. Also, all of the channels of the remote temperature sensing were shielded by the ground plane on either side. Finally, a local bypass capacitor was placed as close to the device as possible.

This TI Design needs to be grouped with a microcontroller in order to do the full thermal foldback that this design is intended for. The microcontroller uses I^2C to communicate with the TMP423-Q1. Because those lines pick up noise very easily, this TI Design is not EMI tested. The ferrite bead and capacitors on the input and output lines are there for when this Design is put together with an automotive microcontroller that has the I^2C lines on the PCB board so they do not pick up noise and cause a failure in EMI and EMC testing.

3 Boost Converter

The TPS92691/TPS92691-Q1 controller is suitable for implementing step-up or step-down LED driver topologies (see Figure 5). In this TI Design, the boost configuration is used. Use the detailed design procedure of the datasheet in Section 8 to select component values for the TPS92691/TPS92691-Q1 device. This section addresses the design process for the boost converter.

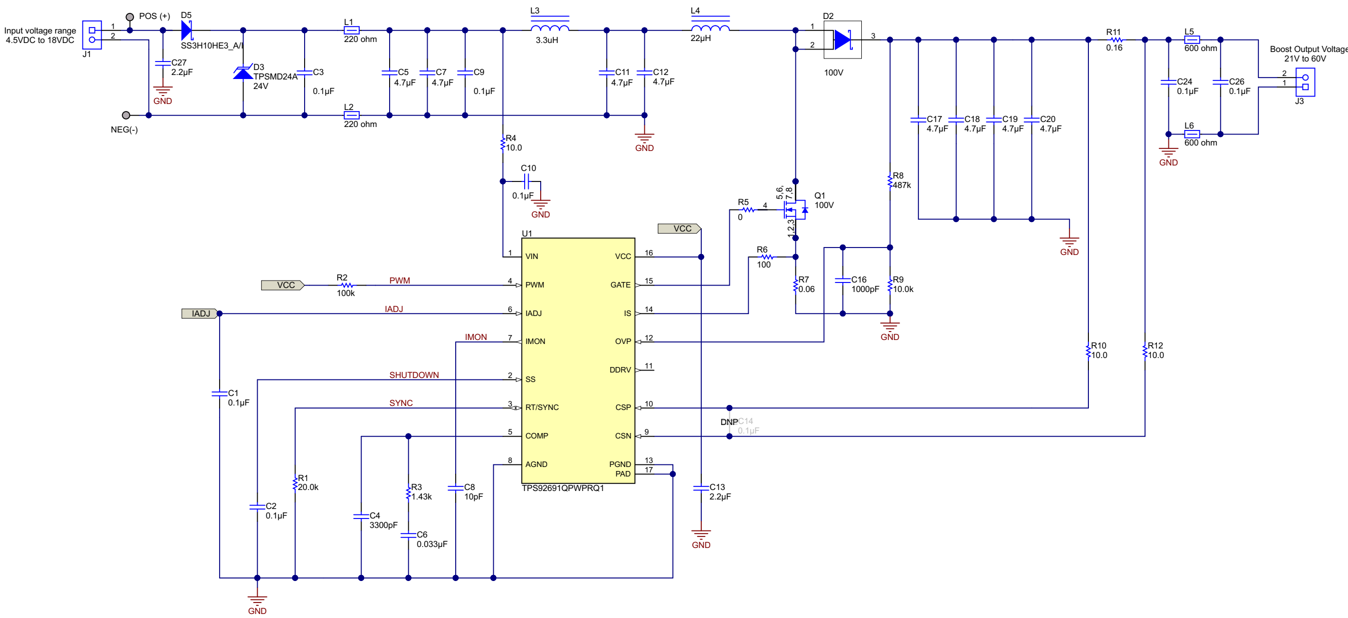

Figure 5. TPS92691-Q1 LED Driver in Boost Configuration

DC-DC converters can couple large amounts of energy (especially at the fundamental switching frequency) back through the battery inputs and into the remainder of the vehicle. This energy is produced because of the switching action of the input-current waveform that is translated into voltage noise by the equivalent series resistance (ESR) of the input capacitors that carry most of this current. A low-pass filter, placed between the input of the module and the DC-DC converters, has been added to attenuate this noise. The low-pass filter also filters incoming noise that enters the system. The low-pass filter can be designed empirically or theoretically (by calculation and simulation). The empirical approach is to design the system without the EMI filter, measure the conducted emissions with a spectrum analyzer, and compare it to the standard that must be passed. Next, calculate the attenuation required to pass at certain frequencies and place the corner frequency of the filter low enough to achieve the desired attenuation.

The theoretical approach is more complicated. Ensure the assumption is that the boost converter is the problem and that the noise generated by the downstream circuitry is to be filtered by the boost inductor or capacitors.

> **NOTE:** The main sources of noise are fundamental at the switching frequency of the boost (400 kHz) and the harmonics. If the amplitude of the noise at that frequency can be estimated and attenuated appropriately, the harmonics can also be attenuated.

The input voltage is the voltage generated by the ripple current through the ESR of the input capacitors. Because ceramic capacitors are used, this ESR is very low (approximately 3 mΩ). The peak amplitude of the input voltage ripple is approximately 2.7 mV (see Equation 8). The concern is the frequency content at 400 kHz, not the time domain.

$$3\ \text{m}\Omega \times 0.9\ \text{A} = 2.7\ \text{mV} \tag{8}$$

Use the Fourier transform of this asymmetric-triangle waveform to find the coefficients and amplitudes of each component frequency. The coefficient of the fundamental for this type of waveform is 0.8. Multiply the coefficient times the time domain amplitude to find the energy at 400 kHz (see Equation 9).

$$0.8 \times 2.7\ \text{mV} = 2.16\ \text{mV} \tag{9}$$

Using Equation 10, convert the product of Equation 9 to dBμV to make it easier to analyze based on the CISPR-25 standards.

$$20 \times \log\left(\frac{2.16\ \text{mV}}{1\ \mu\text{V}}\right) \approx 67\ \text{dB}\mu\text{V} \tag{10}$$

Compare the 67 dBμV to the CISPR-25 specification and calculate how much to attenuate. The CISPR-25 specification does not define a limit at 400 kHz, but the limit at 530 kHz for Class 5 conducted emissions is 54 dBμV (peak). An attenuation of at least 13 dB is required. Make the goal 40-dB attenuation at the switching frequency. Calculate where to place the corner frequency of the filter when attenuation at 400 kHz is known. The second-order low-pass filter has a rolloff of –40 dB per decade. Place the corner frequency at 40 kHz to attain 40 dB of attenuation at 400 kHz. The corner frequency is related to the values of the filter inductor and capacitor, calculated by using Equation 11:

$$2 \times \pi \times f = \frac{1}{\sqrt{L \times C}} \tag{11}$$

Choose an L of 3.3 µH. There is approximately 47 nF, calculating out for C. To keep the ESR low, put two capacitors in parallel and choose 4.7 μF for C12, C14 and C18, C19. Choosing a larger value lowers the corner frequency of the filter, which provides more attenuation at 400 kHz. Also, ceramic capacitors suffer from DC bias effects and operate at a capacitance that is less than their rating. To filter the high-frequency noise content, a 100-nF capacitor is added.

4 Multiple-Channel Temperature Sensing

One of the main focuses in this TI Design is to demonstrate the ability to measure the temperature of the LEDs being driven by the TPS92691-Q1 in order to implement thermal foldback. This is achieved by using the TMP423-Q1 TI temperature sensor. The TMP423-Q1 has three remote-junction temperature-measurement channels and one local die temperature- measurement channel. This device interfaces with an microcontroller that can read and write to its registers. Figure 6 shows the schematic of the temperature sensing section of this TI Design.

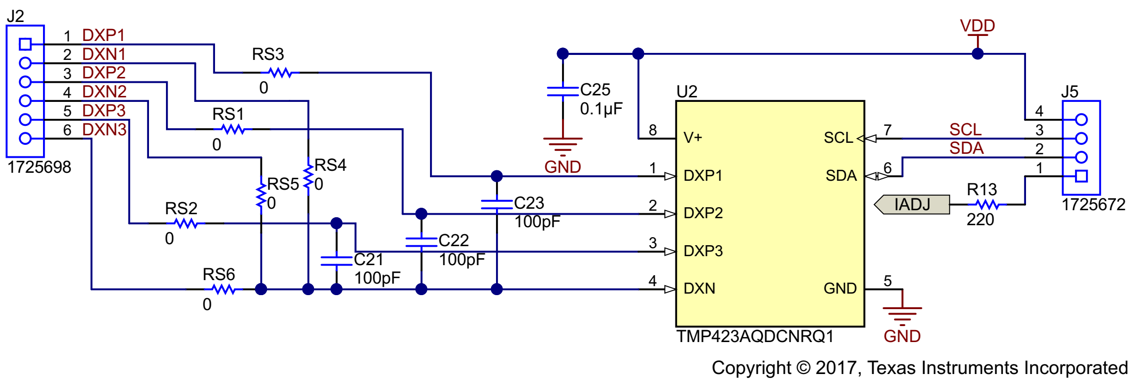

Figure 6. Temperature Sensing Section

4.1 *Remote Temperature Sensing*

The TMP423-Q1 is designed to be used with PNP discrete transistors, as long as the base-emitter junction is used as the remote temperature sense. For this TI Design, the PNP transistors are diode connected so as to reduce the number of physical wires going to each transistor as well as providing a better settling time. Errors in remote temperature sensor readings are typically the consequence of the ideality factor and current excitation used by the TMP423-Q1 versus the manufacturer-specified operating current for the transistors. The TMP423-Q1 gives the option of changing the ideality factor constant for each of its channels by writing to the N Correction registers. Another key aspect is the rate at which the temperature is being measured which is set by the Conversion Rate Register. Note the faster the temperature is measured, the more power the TMP423-Q1 device consumes.

Another key aspect of the remote temperature sensing is the filtering of the lines going to the DXP and DXN pins. The value of these filtering resistors and capacitors is largely based on application and environment. In this TI Design, because the wires going to the diodes are 1-ft long, they would have enough series resistance that adding more did not seem useful. However, the datasheet advises that a 100-pF capacitor be used differentially on each channel. Find more information about the registers and the remote sensing in the TMP423-Q1 datasheet.

4.2 *Thermal Foldback*

With the microcontroller reading the TMP423-Q1 remote temperature sensors, it then must reduce the current through the LEDs accordingly. This is accomplished by sending a PWM signal to the IADJ pin of the TPS92691-Q1. Because of this freedom of the microcontroller to derate the current to meet the LED operating temperature requirements, the thermal fold back response can vary based on the LEDs selected. The microcontroller can choose any temperature to start lowering the current through the LEDs by reading the remote temperature registers and having the output PWM respond accordingly. Note that the sense resistor is the limiting factor on how low the current through the LEDs can go (62.5 mA in this TI Design).

5 Getting Started Hardware

5.1 Hardware

Connect the desired number of LEDs per string at the output screw terminals to get started with the TIDA-01381 board. Figure 7 shows an screenshot of the TIDA-01381 board.

Figure 7. TIDA-01381 With LED Reflectors

5.2 Boost Converter Connector (J3)

The TIDA-01381 is designed to be a boost converter with outputs on LED+ and LED– screw terminals of J3. Note this TI Design is not reverse output protected. Be sure to connect them to the correct plugs. This TI Design was tested using three main reflectors with three LEDs in side of them. Be sure not to violate the maximum output voltage when using a different number of LEDs.

5.3 Input Power (J1, POS(+), NEG(–))

The screw-down connector, J1, marked POS(+) and NEG(–) is for connecting the board to the DC input voltage supply. One other POS(+) and NEG(–) test turret is provided on the board that can also be used. This supports an input voltage of 5 to 18 V.

5.4 Temperature Sensing Connector (J5)

The temperature sensor IC (TMP423-Q1) is placed on the board but all applicable connections are placed outside of the board design. This is so the device can be powered through the "Vcc" screw terminal from the microcontroller or LDO powering microcontroller. Also on the same connector are the two pins "SDA" and "SCL" that do the I^{2}C communication between the microcontroller and the TMP423-Q1. Finally on the connector is the screw terminal "PWM Dimming". This pin connects to the IADJ pin that derates the current through the LEDs.

5.5 Remote Temperature Sensors Connector (J2)

There are three output channels on this connector that correspond to the three remote channels of the TMP423-Q1 device. Each channel of the device needs two physical wires from the remote sensor (diode-connected PNP) to the connector channel. The bottom two screw terminals are for remote temperature sensor channel 1. The "B" stands for base and the "E" stands for emitter which should be connected to the base and emitter of the diode-connected PNP transistor. This works the same way for the other two channels.

5.6 Remote Temperature Sensor

The small boards attached to the heat sinks of the LED reflectors are what is doing the temperature sensing. These boards are diode connected PNP transistors. Using just the one transistors cuts down on the number of wires that would have to come to the small board from three wires (thermistor line, differential line, ground line) to two wires (positive and negative). As explained in the TMP423-Q1 datasheet, the way to connect the diode to the transistor is to connect the collector to the base, which makes up the negative terminal, and connect the emitter to the positive terminal on the TMP423-Q1 device.

With the wires going to the remote temperature sensors being long, unwanted noise may become more an issue. If this becomes the case, the wires should be shielded to prevent the unwanted noise.

6 Testing and Results

This TI Design presents two test results:

1. Efficiency of the boost converter stage
2. Accuracy of temperature measurement

The results of full testing are shown in the following subsections. Note that these tests were done with 1-ft long wires to the temperature sensors.

6.1 Efficiency

For this project, efficiency was measured against output current because of how broadly the output current can change with temperature. The equation used for efficiency was output power over input power. To measure the input power, an ammeter was placed between the car battery and the J1 header and a voltmeter was connected to J1. To measure the output power, an ammeter was placed between LED+ and the load and the voltage was measured from J3.

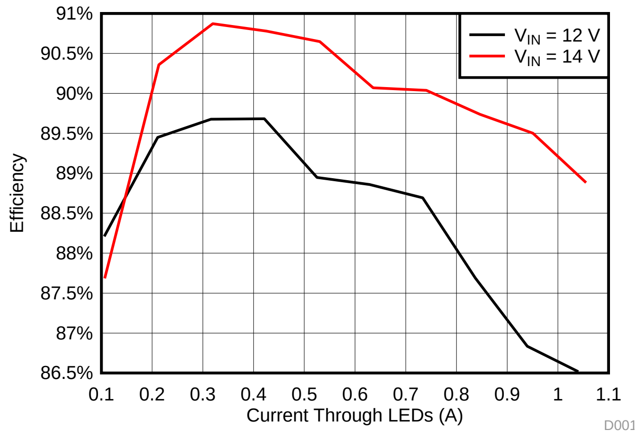

Figure 8. Efficiency versus Output Current

6.2 Accuracy

A very important aspect of this TI Design is how temperature sensing using the TMP423-Q1 compares with temperature sensing using NTC. One of the drawbacks of using an NTC is that over temperature, the current consumption can greatly increase. With the TMP423-Q1, the current consumption of the temperature sensing circuit stays at its typical quiescent current that reflects the rate of conversions for the device (typical max. of 373 μA). Another drawback of the NTC is its inaccuracy over temperature. The test results of this TI Design shows that even at 1-ft long of wire near the switching boost converter wire, the TMP423-Q1 had a 2ºC error. This should be retested for any setup as there are varying factors that can help or hurt the accuracy. Consult the Layout Guidelines section of the datasheet for more information of ways to help the temperature sensing section of this TI Design.

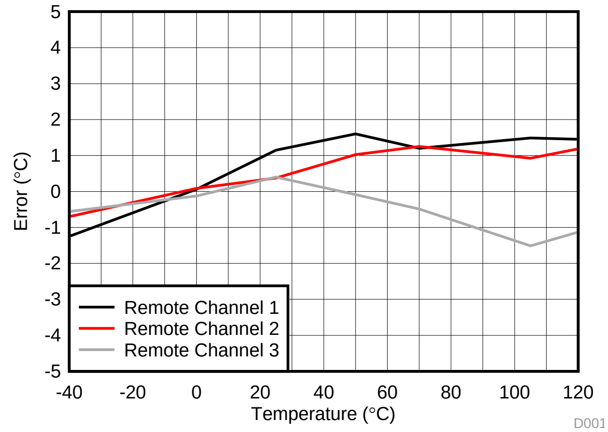

Figure 9. Error versus Temperature

Another test of accuracy is the temperature drift over time. To test this, the design was held at 24.5ºC with all of the channels of the TMP423-Q1 being sampled twice a second. Figure 10 shows the temperature drift over time.

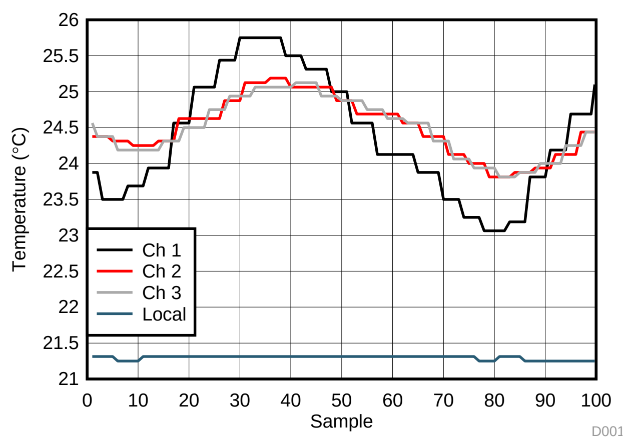

Figure 10. Temperature Drift Over Time

6.3 Other Considerations

The microcontroller was not included in this TI Design. However, when using this design, the test should be run to see the difference between the expected current (that is, the duty cycle of the PWM times the maximum current through the LEDs of 1.138 A) and the actual current going through the LEDs. If there are any discrepancies, the cutoff frequency of the filter from the PWM Dimming pin to the IADJ pin should be decreased and the microcontroller should be checked for the accuracy of its PWM signal being produced.

In the application of this TI Design, the temperature sensing lines might have to be longer. Take care because the longer the wires are the more noise they will pick up, causing the temperature measurement to be distorted.

7 Design Files

7.1 Schematics

To download the schematics, see the design files at TIDA-01381.

7.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01381.

7.3 PCB Layout Recommendations

7.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01381.

7.4 Altium Project

To download the Altium project files, see the design files at TIDA-01381.

7.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01381

7.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01381.

8 References

1. Texas Instruments, *TMP423-Q1 ±1°C Remote and Local TEMPERATURE SENSOR*, TMP423-Q1 Datasheet (SBOS398)
2. Texas Instruments, *TPS92691/-Q1 Multi-Topology LED Driver With Rail-to-Rail Current Sense Amplifier*, TPS92691-Q1 Datasheet (SLVSD68)
3. Texas Instruments, *TPS92691 Boost and Boost-to-Battery LED Driver Evaluation Board*, TPS92691 User's Guide (SLVUAO7)

8.1 Trademarks

All trademarks are the property of their respective owners.

9 About the Author

CAMERON PHILLIPS is an Applications Rotation Program participant at Texas Instruments where he is responsible for developing reference design solutions for the Automotive Body and Lighting segment. Cameron earned his bachelor of science in electrical engineering from Texas A&M University.

Revision History

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

Changes from Original (January 2017) to A Revision **Page**

- Changed title 1
- Changed caption for *Figure 7* 13