

TI Designs

CISPR-25 Tested, Boost LED Driver Reference Design for Automotive Aftermarket Lighting Designs



Design Overview

This TI Design showcases a TPS92691 LED driver solution that can be used in a variety of automotive and vehicle aftermarket lighting applications. The boost topology is intended for direct-to-battery, single-stage LED driver designs which result in simpler and cost-effective lighting solutions. Additional design flexibility includes analog and PWM dimming support as well as built-in continuous LED current monitoring for fault detection and protection. EMI filtering has been included and designed to meet CISPR-25, Class 3 conduction requirements.

Resources

PMP15003	Design Folder
TPS92691-Q1	Product Folder
TPS92691 SEPIC EVM	Tools Folder
TPS92691 Boost and Boost-to-Battery EVM	Tools Folder
TPS92961 Boost and SEPIC P-Spice Model	Tools Folder

Design Features

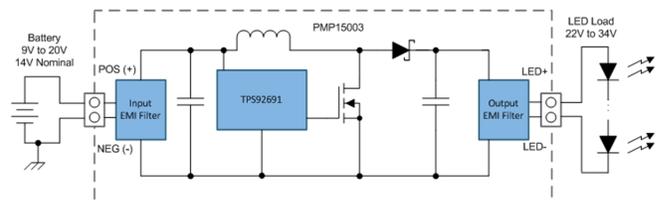
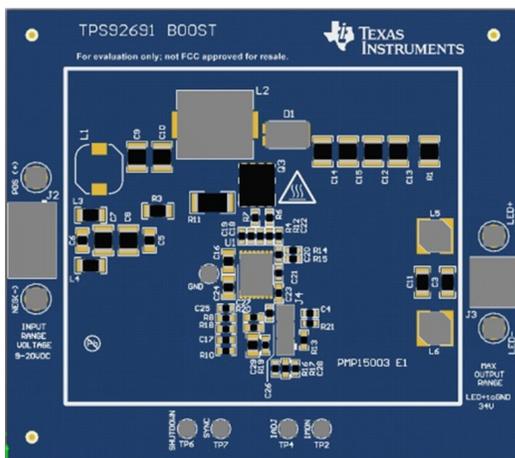
- Optimized for Aftermarket Lighting Applications
- CISPR-25 Tested EMI
- Stays Out of AM Band
- Operation Through Warm Crank
- Analog and PWM Dimming
- Continuous LED Current Monitoring Output
- Overvoltage Protection and Input Undervoltage Lockout

Applications

- Automotive Aftermarket Lighting:
 - Light Bars
 - Law Enforcement, Fire, and EMS Scene Lighting
 - Recreational Vehicle, ATV, and UTV Auxiliary Lighting
- Agricultural, Marine, and Heavy Industry Lighting



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1 System Overview

1.1 System Description

Styling, energy efficiency, and longevity are all factors that are causing widespread adoption of light emitting diodes in place of incandescent light bulbs in automotive applications. A number of light-emitting diode lighting aftermarket products further enhance driver and passenger experiences. Intense competition puts pressure on aftermarket lighting product vendors to reduce time to market, and offers high quality in terms of EMI, thermal efficiency, and light quality.

The PMP15003 reference design gives a simple, easy to adopt implementation for a high-output accuracy boost LED driver with integrated current monitoring. This design uses the TPS92691 multi-topology controller. The implemented circuit topology has an input voltage range of 4.5 V to 20 V, which encompasses cold crank conditions (ISO7637-2). This design meets CISPR-25 Class 3 electromagnetic interference (EMI) standards, and the set switching frequency for the controller is set outside the AM frequency band. External frequency synchronization capability on the TPS92691 makes this design scalable for use in higher power applications with multiple LED strings.

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
INPUT PARAMETER						
V_{VIN}	Input voltage range	—	7	—	20	V
V_{UVLO}	Input UVLO setting	—	—	4.4	—	V
OUTPUT PARAMETER						
V_F	LED forward voltage	—	—	3.4	—	—
n_{LED}	Number of LED in series	—	—	10	—	—
V_{VOUT}	Output voltage range	—	22	—	34	—
I_{LED}	Output current	—	—	1	—	—
RR	LED current ripple ratio	—	—	—	1.5	—
$P_{O(MAX)}$	Maximum output power	—	—	—	34	—
	Analog dimming range	$V_{IADJ} = 140 \text{ mV to } 1.4 \text{ V}$	10:1	—	—	—
SYSTEM SPECIFICATIONS						
$V_{O(OV)}$	Output overvoltage protection level	—	—	62	—	V
$V_{O(HYS)}$	Output overvoltage protection hysteresis	—	—	10	—	V
$\Delta I_{L(PP)}$	Inductor current ripple	—	—	960	—	mA
$\Delta V_{IN(PP)}$	Inductor voltage ripple	—	—	20	—	mV
F_{SW}	Switching frequency	—	—	390	—	kHz
t_{SS}	Soft start period	—	—	10	—	ms
V_{IMON}	IMON pin voltage	$I_{LED} = 1 \text{ A}$	—	1.4	—	V
	LED open and short detect	—	—	Yes	—	—
η	Efficiency	Input voltage = 14 V, Output voltage = 34 V (ten LEDs)	—	92%	—	—
	EMI	—	—	—	—	—
T_A	Ambient temperature range	—	–40	—	125	°C
BASEBOARD CHARACTERISTICS						
	Form factor	77.47 mm × 68.58 mm	—	—	—	—
	No. of layers	2	—	—	—	—
	Height	10	—	—	—	—

1.3 System Design Theory

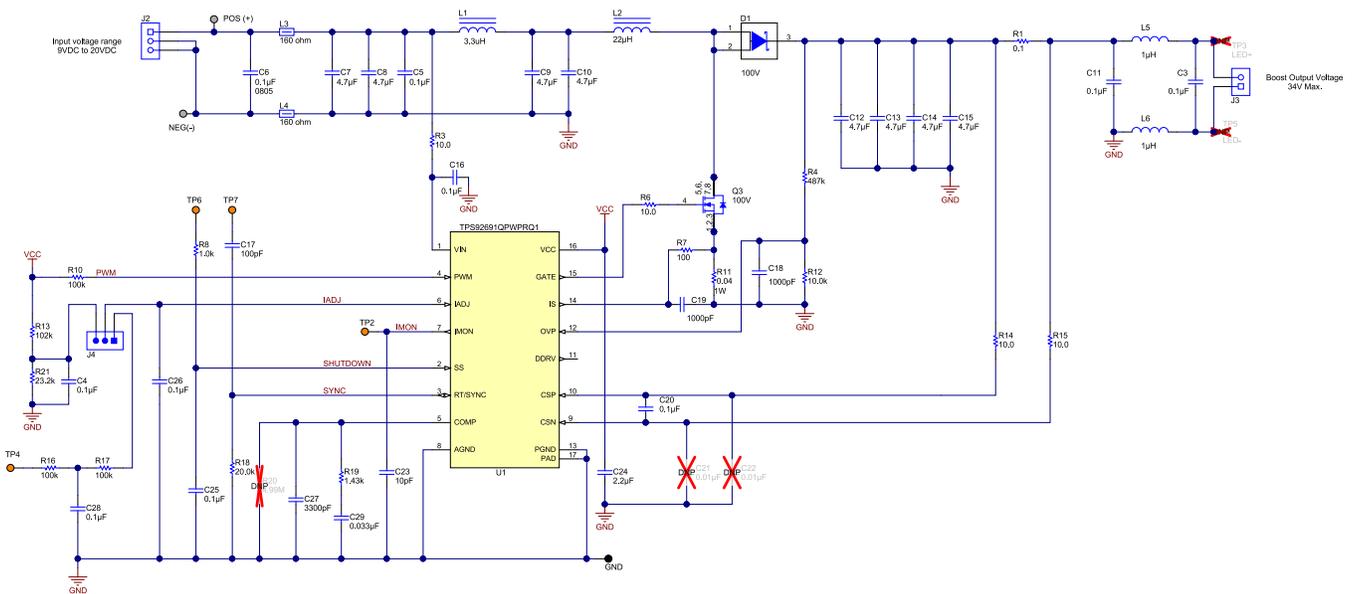


Figure 1. PMP 15003 Schematic

This design consists of a high performance LED controller device with an external field-effect transistor (FET) configured in the boost (step-up) topology, with an EMI filter at the output. The V_{IN} range for this design is from 4.5 V to 20 V. This range makes the system functional during crank conditions as described by the ISO7637-2 specification. With a maximum possible output voltage of 34 V, this design can be used for lighting a string of up to ten high brightness LEDs (assuming an LED forward voltage of 3.2 V). The design allows for a maximum of 1 A of output current and thus maximum output power can be 34 W.

The main power inductor (L2) has been carefully selected to ensure that the LED controller works in continuous-conduction mode over a specific power range and meets the tight output current ripple specification with a reasonable amount of output capacitance. For this design, the inductor value was calculated to ensure operation in continuous conduction mode (CCM) down to $\frac{1}{4}$ of the maximum output power of 34-W using the nominal input voltage of 14 V. This calculation results in a value of approximately 17 μ H. To account for inductor tolerances, a 22 μ H inductor value was selected. The input capacitor (C7-C10) and output capacitor (C12-C15) are selected to meet input ripple voltage and output ripple current specifications respectively, as listed in the [Table 1](#) table. At the nominal input voltage of 14 V and 50 mV of input voltage ripple, the calculated input capacitor value is approximately 6 μ F. To compensate for tolerances, a total of 10 μ F was selected directly at the input (not including extra EMI filtering). 24 μ F. To ensure less than a 1.5% LED current ripple ratio, the calculated output capacitance has been set to approximately 24 μ F. In total, 40 μ F has been selected to account for tolerances and capacitance drop as a result of bias voltage. For a detailed explanation on how to select these component values to meet design specifications, see [TPS92691-Q1 Multi-Topology LED Driver With Rail-to-Rail Current Sense Amplifier \(SLVSD68\)](#).

1.4 Switching Frequency and Synchronization (RT/SYNC)

The default switching frequency set using the RT and SYNC pins is 390 kHz, which is outside the AM band. This setting can be changed by adjusting R18. This signal is coupled through C17 and sets the switching frequency to the external signal frequency. External signal frequencies can sync multiple TPS92691s in applications where more than 34-W of power is required.

1.4.1 Output Overvoltage Protection (OVP)

As automotive environments are harsh, good designs incorporate protection features against all scenarios. This 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. The default maximum value the output voltage will reach approximately 62 V with approximately 10 V of hysteresis to prevent going above the 65 V absolute maximum ratings of the TPS92691. The following equations can calculate and adjust the levels:

$$R4 = \frac{V_{OV(HYS)}}{20 \times 10^{-6}} = \frac{10 \text{ V}}{20 \times 10^{-6}} = 500 \text{ k}\Omega$$

This design uses a 487-k Ω resistor. R12 is calculated using:

$$R12 = R4 \times \left(\frac{1.24 \text{ V}}{V_{O(OV)} - 1.24 \text{ V}} \right) = 487 \text{ k}\Omega \times \left(\frac{1.24 \text{ V}}{62 \text{ V} - 1.24 \text{ V}} \right) = 9.94 \text{ k}\Omega$$

This design uses a resistor value of 10-k Ω .

1.4.2 Analog Dimming (IADJ) and Programming LED Current

This design targets lighting systems that only have an ON and OFF mode. For this level of functionality, pulse-width modulation dimming is not required. Not using PWM dimming leads to increased EMI performance, which in turn reduces time to market. Using the IADJ pin, the default output current level for this design equals 1 A. The IADJ voltage is set to 1.4 V using R13 and R21 to form a resistor divider from VCC. This results in a current sense voltage (CSP-CSN) of 100 mV. This divider can be disconnected and a voltage between 0 V and 1.4 V can be applied directly to the IADJ pin to provide an analog dimming function.

The output current default setting can be changed by adjusting the IADJ pin resistor divider and the current sense resistor value. To change the resistor divider or resistor value, use the following equations:

$$V_{(CSP-CSN)} = \frac{V_{IADJ}}{14} = \frac{1.4 \text{ V}}{14} = 100 \text{ mV}$$

$$R1 = \frac{V_{(CSP-CSN)}}{I_{LED}} = \frac{100 \text{ mV}}{1 \text{ A}} = 100 \text{ m}\Omega$$

(1)

The current sense voltage ($V(\text{CSP-CSN})$) can be adjusted between 0 mV and 172 mV. To balance current accuracy and efficiency, this design uses a current sense voltage of 100 mV. To change the current sense voltage, R13 remains at the selected value of 102 k Ω (or changed as desired). R21 is calculated using [Equation 2](#):

$$R21 = R13 \times \left(\frac{V_{\text{IADJ}}}{V_{\text{VCC}} - V_{\text{IADJ}}} \right) = 102 \text{ k}\Omega \times \left(\frac{1.4 \text{ V}}{7.5 \text{ V} - 1.4 \text{ V}} \right) = 23.4 \text{ k}\Omega \quad (2)$$

R21 can be replaced with a NTC thermistor for thermal foldback, as shown in *TPS92691/-Q1 Multi-Topology LED Driver With Rail-to-Rail Current Sense Amplifier* ([SLVSD68](#)). This provides immediate thermal foldback for elevated temperatures. A zener diode can be placed in parallel with R21 to provide a nominal current level until the NTC is at a low enough resistance to pull the IADJ pin low, which enables a tailored break point in the thermal foldback. The NTC must be placed at the LED load for best thermal foldback results.

1.4.3 Current Monitoring (IMON)

The TPS92691 provides integrated current monitoring to signal an undercurrent or overcurrent event. The IMON pin voltage is 14 times the current sense voltage (CSP-CSN). This IMON output is brought to connector TP2 and can detect a fault and disable the device, as shown in *TPS92691/-Q1 Multi-Topology LED Driver With Rail-to-Rail Current Sense Amplifier* ([SLVSD68](#)).

1.4.4 PWM Dimming Capability

This design has been simplified for lower BOM count and cost by removing the PWM dimming circuitry, disconnecting FET, and relying only on analog dimming. This allows for lower cost output filtering using two small low cost inductors. If PWM dimming is desired, this circuitry can be added back into the design by referring to *TPS92691/-Q1 Multi-Topology LED Driver With Rail-to-Rail Current Sense Amplifier* ([SLVSD68](#)). If PWM dimming is used, the output filter inductors must be replaced with a common-mode filter to reduce current spikes and ringing.

1.4.5 Thermal Protection

Internal thermal protection circuitry protects the controller in the event the maximum junction temperature is exceeded. Typically at +175°C, the controller shuts down and protects the circuitry in the reference design.

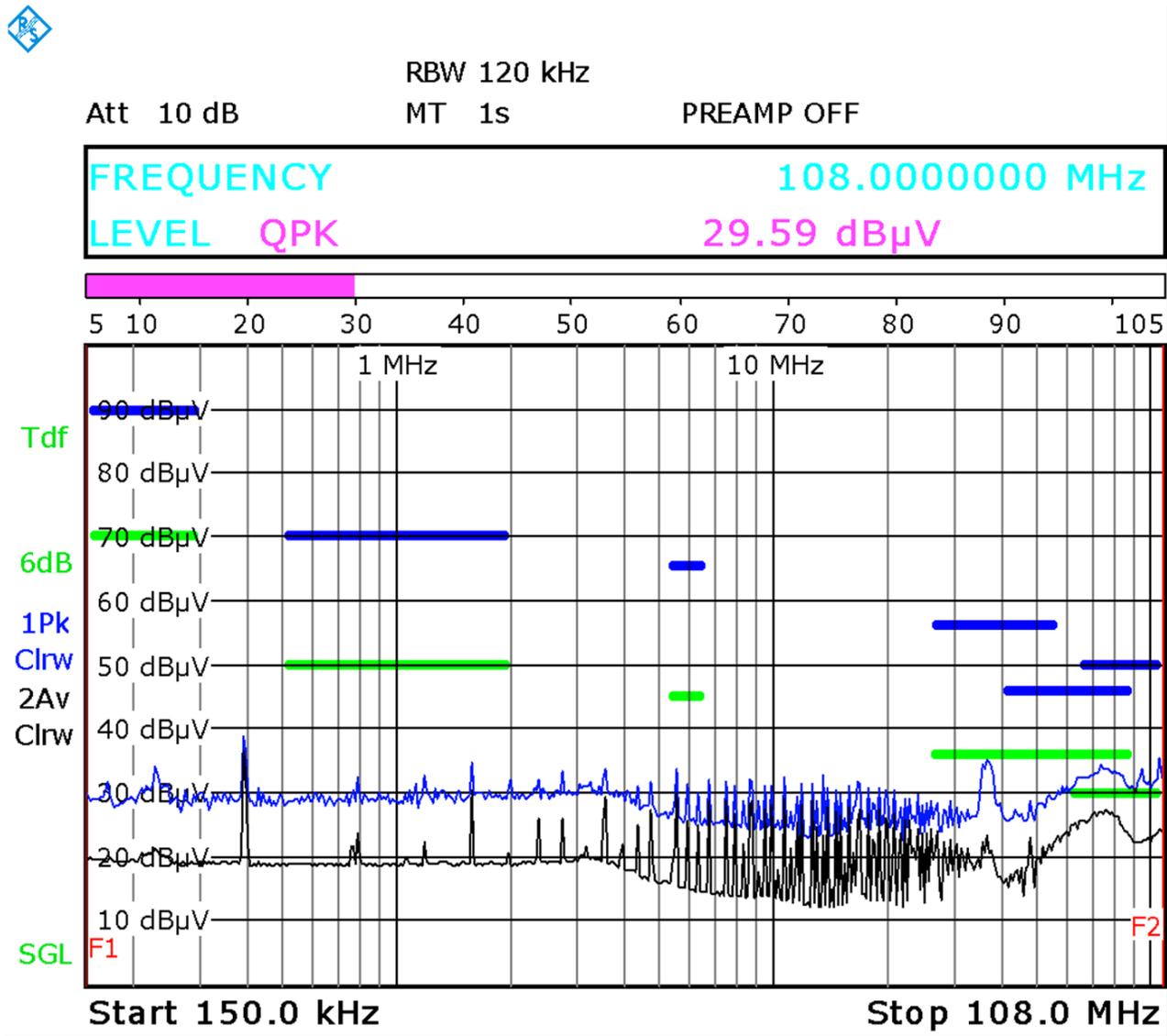
1.5 Designing for Low EMI

- CISPR-25 Overview
- Layout Guidelines
- EMI Filter Design
- Other Tips and Tricks

1.5.1 CISPR-25 Overview

CISPR-25 is the automotive EMI standard that most original equipment manufacturers base requirements on. The standard is titled *Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers*. The purpose of the standard is to limit the amount of emissions from a subsystem in a few important frequency bands, and to ensure the subsystem does not interfere with other systems that intentionally operate (that is, receive) in those bands. Standards like CISPR-25 are specifically designed to avoid interference between systems by setting acceptable limits on these systems.

[Figure 2](#) shows the conducted EMI scan for the circuit at the nominal 14-V input voltage and running a full power load of 34 V at 1 A of LED current. The blue trace is a peak scan and the blue lines denote the peak limits for CISPR-25 Class 3. The black trace is an average scan, and the green lines denote the average limits for CISPR-25 Class 3. The scan covers the entire conducted and radiated frequency range of 150 kHz to 108 MHz.



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Figure 2. CISPR-25 Class 3 Conducted EMI Scan (Pre-Compliance Data)

1.5.2 Layout Guidelines

- The performance of the switching regulator depends as much on the layout of the PCB as the component selection. Following guidelines maximizes noise rejection and minimizes the generation of EMI within the circuit.
- Discontinuous currents are the currents most likely to generate EMI. Take care when routing these paths. In the TPS92691 boost regulator, the discontinuous current flows through the output capacitor COUT, diode, D, N-channel MOSFET, Q1, and the current sense resistor, RIS. In Buck-Boost regulator, both loops are discontinuous and must be carefully laid out. These loops must be kept as small as possible, and the connection between all the components must be short and thick to minimize parasitic inductance. In particular, the switch node (where L, D, and Q1 connect) must be large enough to connect the components. To minimize excessive heating, large copper pours can be placed adjacent to the short current path of the switch node.

- CSP and CSN traces must be routed together with Kelvin connections to the current sense resistor being as short as possible. If needed, use common-mode and differential mode noise filters to attenuate switching and diode reverse recovery noise from affecting the internal current sense amplifier.
- The COMP, IS, OVP, PWM, and IADJ pins are all high-impedance inputs that couple external noise easily. Therefore, the loops containing these nodes must be minimized whenever possible.
- In some applications, the LED or LED array can be far away from the TPS92691 or on a separate PCB connected by a wiring harness. When using an output capacitor and the LED array is large or separated from the rest of the regulator, the output capacitor must be placed close to the LEDs to reduce the effects of parasitic inductance on the AC impedance of the capacitor.
- The TPS92691 has an exposed thermal pad to aid power dissipation. Adding several vias under the exposed pad helps conduct heat away from the device. The junction-to-ambient thermal resistance varies with application. The most significant variables are the area of copper in the PCB and the number of vias under the exposed pad. The integrity of the solder connection from the device exposed pad to the PCB is critical. Excessive voids greatly decrease the thermal dissipation capacity.

1.5.3 EMI Filter Design

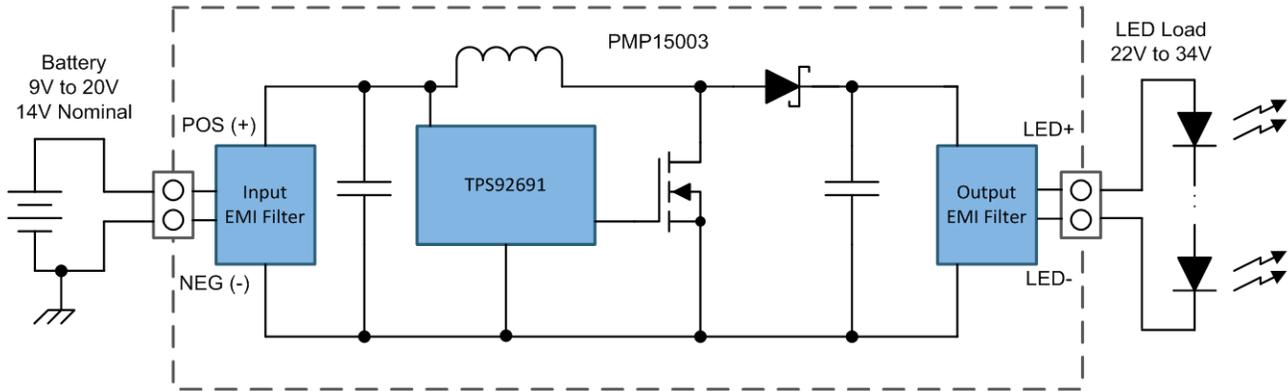
The input EMI filter consists of a differential mode PI filter formed by the input capacitors (C7-C10) and the input inductor (L1). Common-mode noise on the input is attenuated by the ferrite beads (L3 and L4), which present low DC resistance, but present high resistance at high frequencies where common-mode noise is the most common. Differential mode noise filtering on the output is typically suppressed by the output capacitors, assuming low ESR ceramics are used as in this design. To attenuate high frequency common-mode noise on the output, the L5 and L6 inductors are placed in series with LED+ and LED-. For more information on EMI filter design, refer to TI literature numbers [SNVA489](#) and [SNVA538](#).

1.5.4 Other Tips and Tricks

This design has been produced for a balance of small size, high efficiency, and good performance for a maximum of 34 W of output power. Dimming range may be increased by increasing the current sense voltage to the maximum level for full output power and changing the current sense resistor at the expense of lower efficiency at full power. Output current may be increased for lower stack voltages or decreased for higher stack voltages as desired if the maximum output power remains within the maximum 34-W range. Higher power levels may be achieved, but require a larger inductor with a higher saturation current rating, a larger case size FET for better power dissipation, or better heat sinking using thicker or more copper layers to dissipate the additional heat generated.

Higher power levels need increased EMI filtering to pass CISPR-25 Class 3 limits. This may include more input and output capacitance, increased ferrite bead resistance at a high frequency, or increased output inductance for common-mode noise. Slowing switching edges and reducing high frequency ringing due to switching edges helps reduce noise in switching regulators. Common methods to reduce noise in this manner include increasing the gate resistance of the power MOSFET, using a ferrite bead in series with the power MOSFET or output diode, or using an RC snubber across the power MOSFET, output diode, or both.

2 Block Diagram



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Figure 3. Block Diagram for PMP15003

3 Highlighted Products

3.1 TPS92691

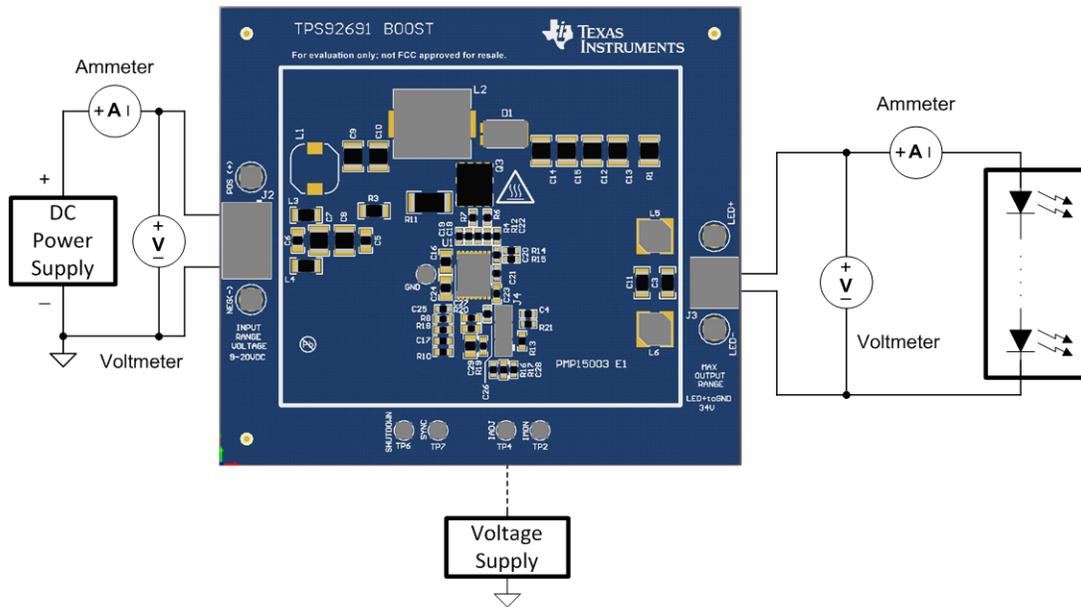
The TPS92691-Q1 is a versatile LED controller that supports a range of step-up or step-down driver topologies. The device implements a fixed-frequency control technique with programmable switching frequency, slope compensation, and soft-start timing. This device incorporates a high voltage (65-V) rail-to-rail current sense amplifier that directly measures LED current using a high-side and low-side series sense resistor. The current sense amplifier is designed to achieve low input offset and attain better than $\pm 3\%$ LED current accuracy over a junction temperature range of $+25^{\circ}\text{C}$ to $+140^{\circ}\text{C}$ and an output common-mode voltage range of 0 V to 60 V.

LED current can be independently modulated using analog or PWM dimming techniques. Varying the voltage from 140 mV to 1.4 V across the high impedance analog adjust (IADJ) input achieves a linear analog dimming response with a 10:1 range. The device achieves 15:1 dimming when the IADJ pin is increased to 2.25 V, and the current sense resistor does not exceed the maximum 34-W of output power. PWM dimming of the LED current occurs by modulating the PWM input pin the desired duty cycle and frequency. Optional DDRV gate driver output enables series FET dimming functionality to achieve a 1000:1 contrast ratio.

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

4 Test Setup

The test setup used is shown in Figure 4 and Figure 5. Four digital multimeters (DMMs) measure input voltage, input current, output voltage, and output current. Input voltage, output voltage, and LED current are each measured with an Agilent 34401A DMM, while the input current is measured using a Fluke 79III true RMS multimeter that measures up to 10 A. The input supply used is an Agilent E3634A rated for up to 25 V at 7 A. An external low current voltage supply connects directly to the IADJ pin for the analog dimming profile. This provides the data for efficiency, line regulation, and analog dimming measurements found in Section 4.1.



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Figure 4. Test Connections

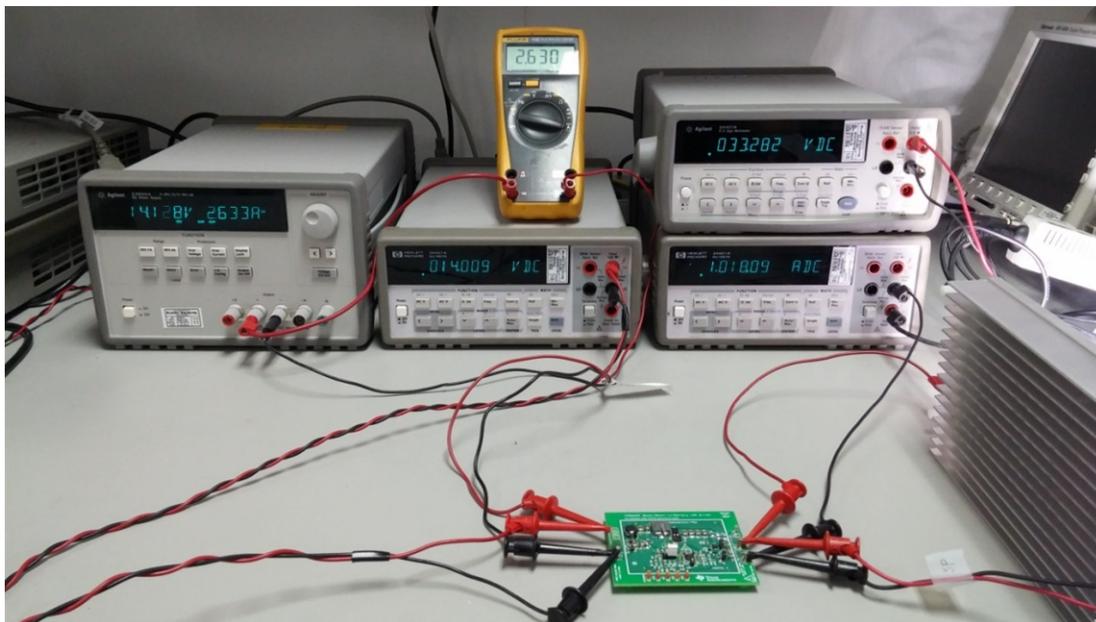


Figure 5. Bench Test Setup

4.1 Test Data

Efficiency, line regulation, and analog dimming data was obtained at the full output power with a 34-V LED stack at 1-A LED current. Scope shots are for the full output power of 34 V at 1 A, and a nominal input voltage of 14 V.

4.2 Efficiency

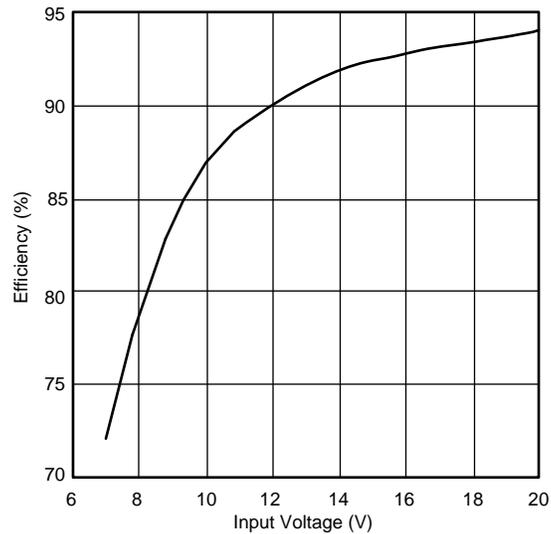


Figure 6. Efficiency vs Input Voltage

4.3 Line Regulation

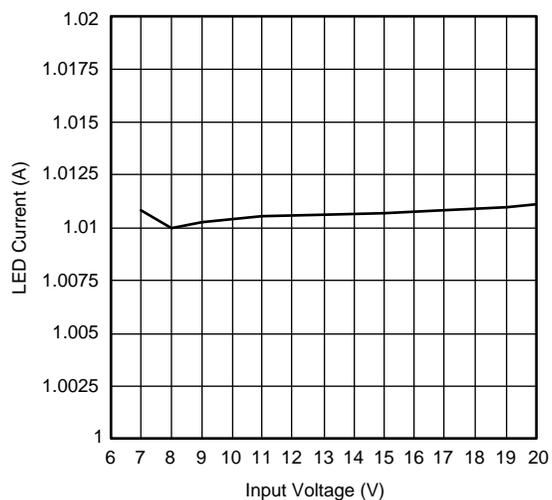


Figure 7. LED Current vs Input Voltage

LED current variation over the entire input voltage range is approximately 1 mA or 0.1%.

4.4 Analog Dimming

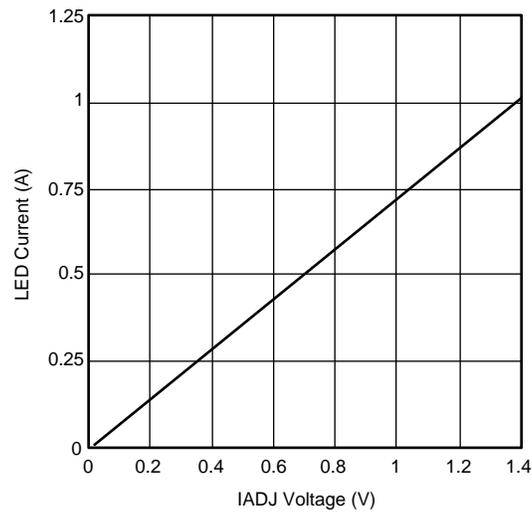


Figure 8. LED Current vs IADJ Pin Voltage

LED current is linear versus the applied IADJ voltage from full power ($V_{IADJ} = 1.4 \text{ V}$) to a 10:1 dimming ratio ($V_{IADJ} = 140 \text{ mV}$). Linearity is still present below 140 mV, but error amplifier offsets can cause some variation from circuit to circuit below 140 mV.

4.5 Start-Up Waveform

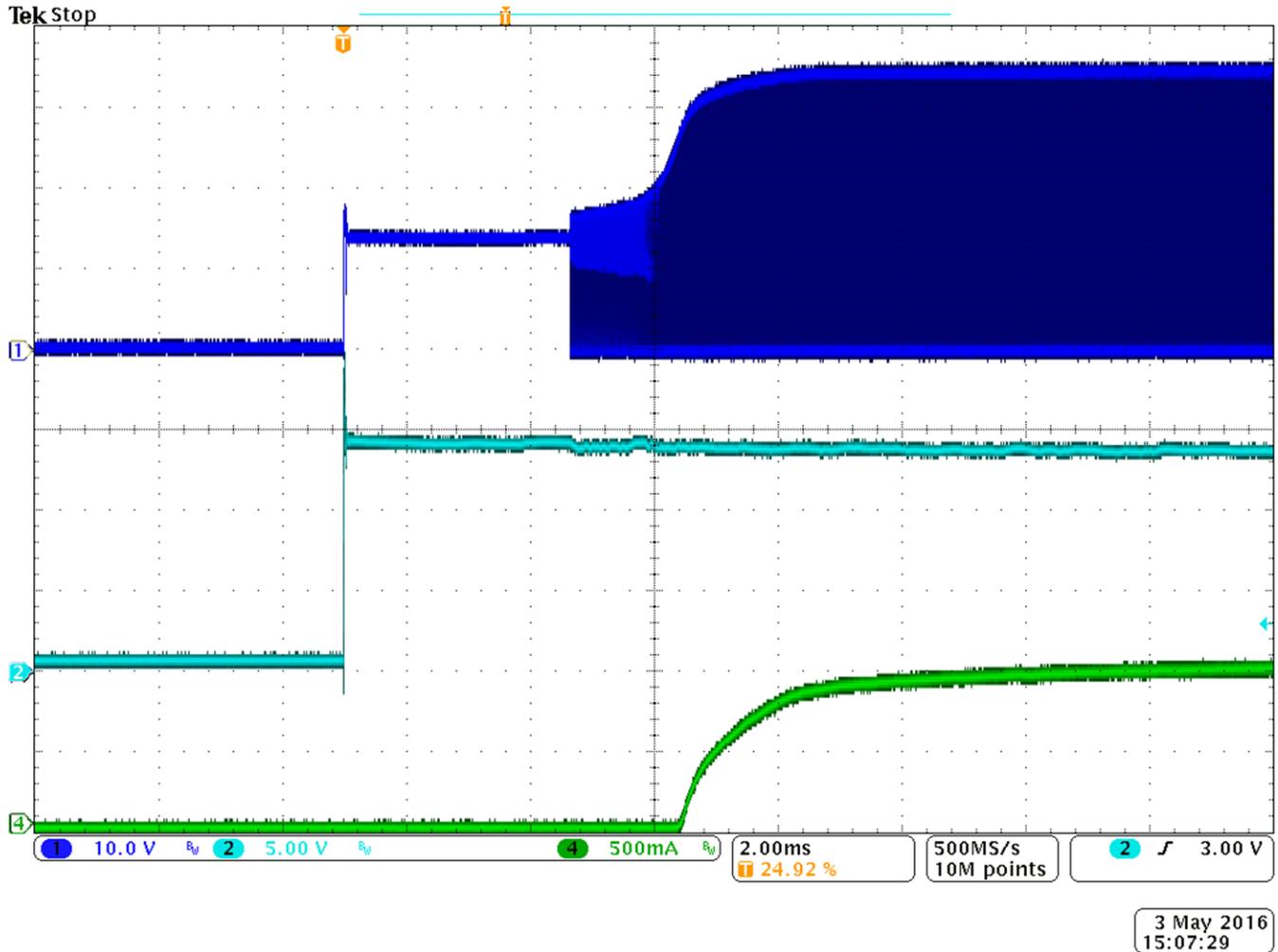


Figure 9. Top = Switch Drain, Middle = Input Voltage, Bottom = LED Current

4.6 Switching Waveform

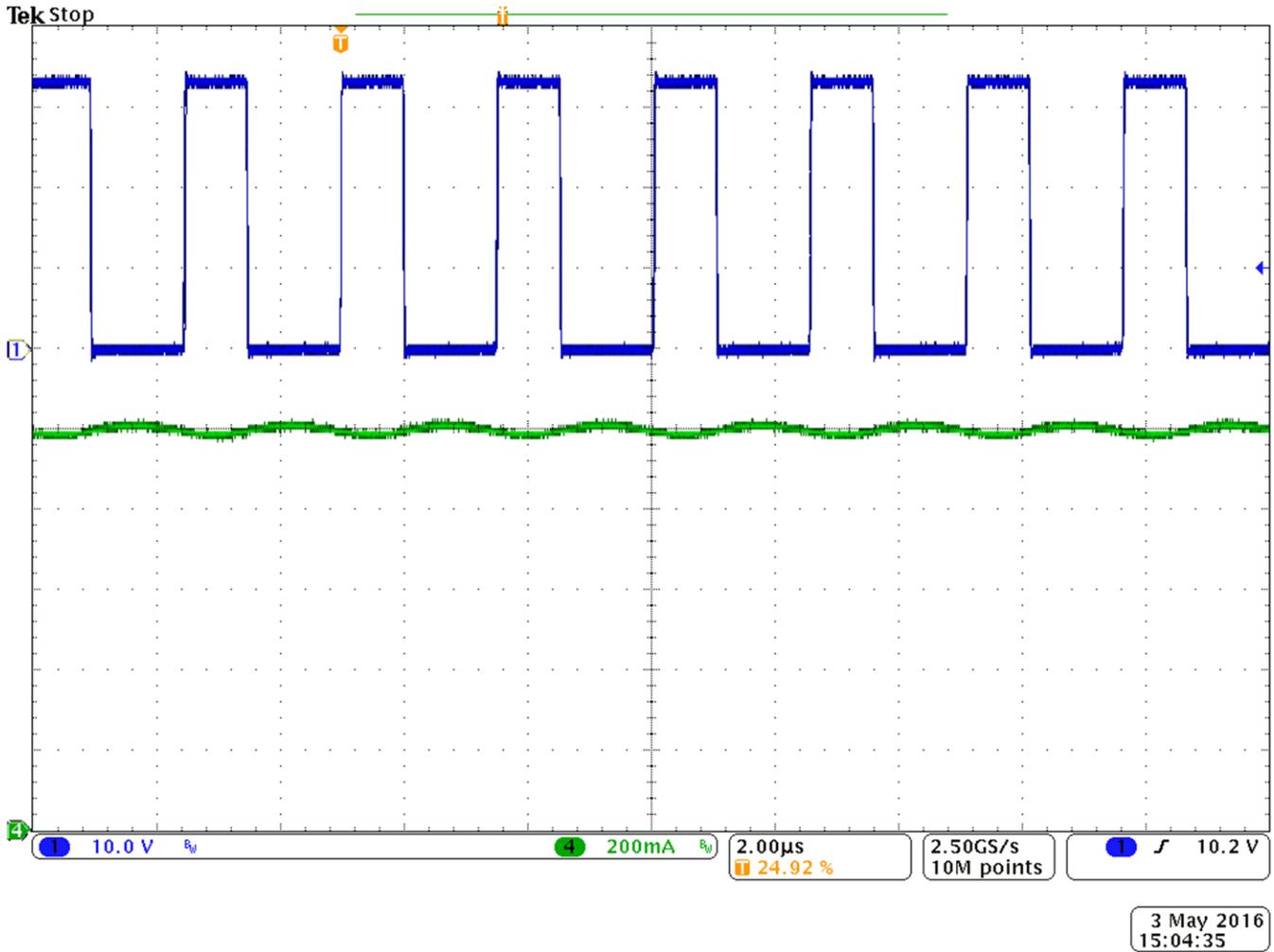


Figure 10. Top = Switch Drain, Bottom = LED Current

5 Design Files

5.1 Schematics

To download the schematics, see the design files at [PMP15003](#).

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [PMP15003](#).

5.3 PCB Layout Recommendations

As with any switching regulator, layout is important to avoid noise issues and misbehavior, as well as reducing EMI. The switch node connection of L2, D1, and Q3 must be as short and direct as possible. The connection between D1 and the output capacitors must be short and direct. The ground connections for the TPS92691, R11, and the output capacitors must be close together and have a direct ground path to each other. The forward currents during both the switch ON and OFF cycles have a ground return current that follows the path of least impedance. Since the currents are switching at relatively high frequencies, this return path follows the forward path as closely as possible. Provide this path with the use of a ground plane that is not interrupted by cuts in the plane for other traces.

5.3.1 Board Image: 3D Rendering and Thermals

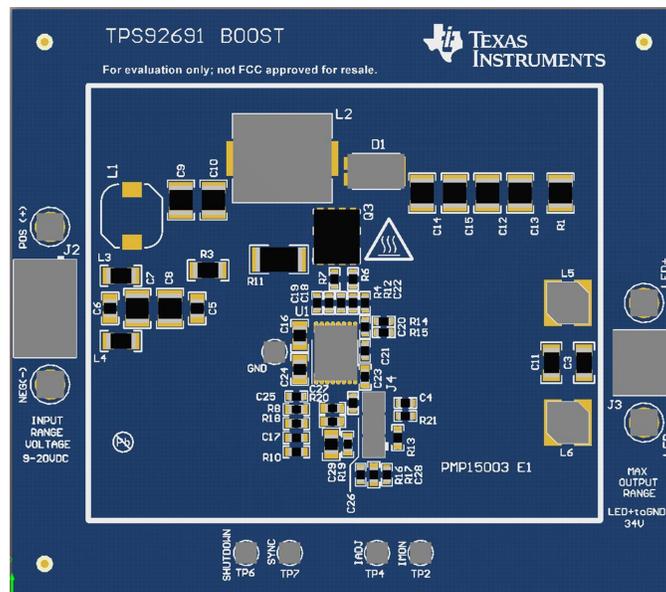


Figure 11. 3D Top View

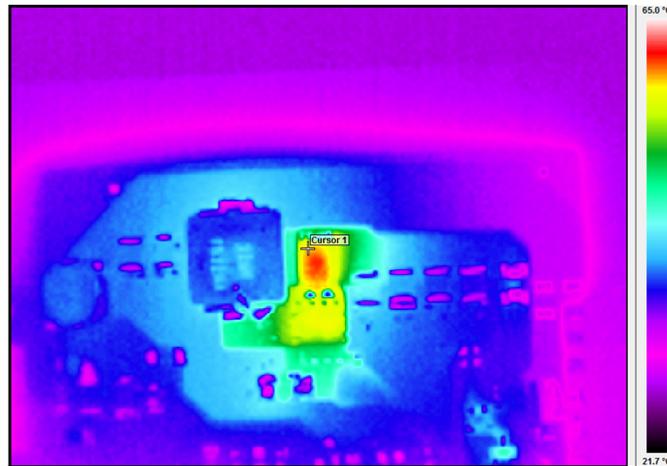


Figure 12. Steady State Thermal View, L2, D1, Q3, and R11 (Power Components)

5.3.2 Layout Prints

To download the layout prints for each board, see the design files at [PMP15003](#).

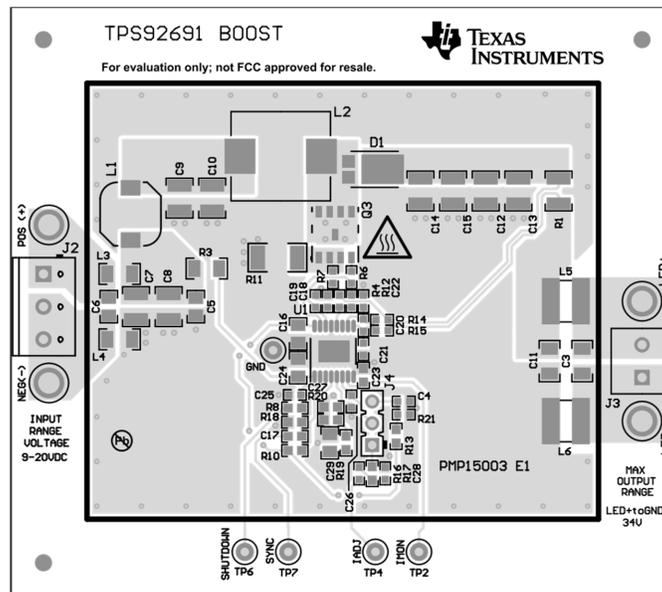


Figure 13. Top Layer and Top Silkscreen

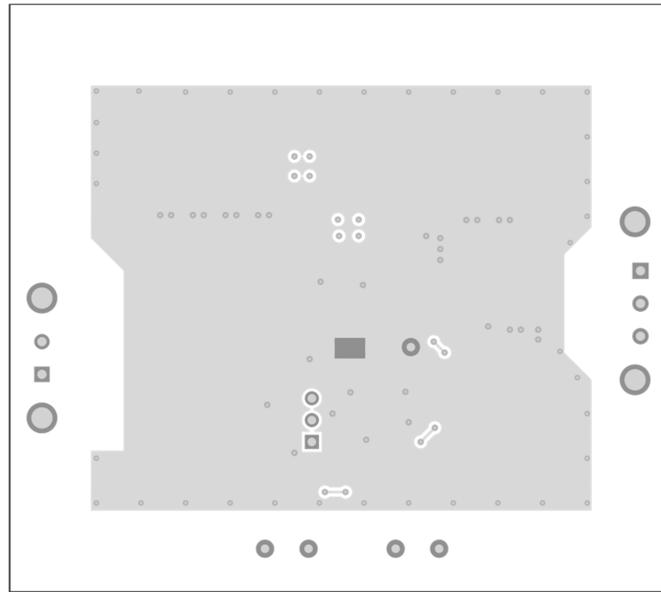


Figure 14. Bottom Layer

5.4 Altium Project

To download the Altium project files, see the design files at [PMP15003](#).

5.5 Gerber Files

To download the Gerber files, see the design files at [PMP15003](#).

5.6 Assembly Drawings

To download the assembly drawings, see the design files at [PMP15003](#).

6 Software Files

To download the software files, see the design files at [PMP15003](#).

7 References

1. Texas Instruments, *TPS92691/-Q1 Multi-Topology LED Driver With Rail-to-Rail Current Sense Amplifier (SLVSD68)*.
2. Texas Instruments, *Boost and Boost-to-Battery Evaluation Module (SLVUA07)*.
Texas Instruments, *Reinforced Isolation 3-Phase Inverter With Current Voltage Design Guide (TIDUBX1)*.
3. CISPR-25, Edition 3.0 2008-03, *Vehicles, Boats and Internal Combustion Engines – Radio Disturbance Characteristics – Limits and Methods of Measurement for the Protection of On-Board Receivers*
4. ISO 7637-2:2004 *Road Vehicles – Electrical Disturbances from Conduction and Coupling – Part 2: Electrical Transient Conduction Along Supply Lines Only (Section 5.6)*
5. ISO 16750-2:2010 *Road Vehicles – Environmental Conditions and Testing for Electrical and Electronic Equipment – Part 2: Electrical Loads (Section 4.6)*
6. Texas Instruments, *WEBENCH® Design Center, Design and Simulation Tools (<http://www.ti.com/webench>)*

8 About the Author

CLINTON JENSEN is an Applications Engineer at Texas Instruments with the Lighting Power Products group responsible for industrial and automotive LED lighting. Clint earned a BS degree in electrical engineering from Virginia Polytechnic Institute and State University in Blacksburg, VA and currently has 18 years of power supply design experience.

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