TI Designs: TIDA-050008
ADAS Power Reference Design with Improved Voltage Supervision

Description

This reference design provides an automotive power solution with additional precision voltage supervision and window watchdog for safety MCUs in Advanced Driver Assistance Systems (ADAS). These systems can control driving functions, such as automated emergency brake, lane keep assist and adaptive cruise control. High accuracy voltage detectors monitors each rail for improved supervision that can help customers achieve their functional safety goals. This design can support system supply currents up to 5 A at 3.3 V. The design can operate off an automotive battery, withstand reverse battery conditions, and support start-stop and cold-crank down to a 3.5-V input. All switching frequencies in this solution are fixed and above 2 MHz (outside AM radio band). This reference design also provides results for conducted emissions tests for CISPR 25 Class 5.

Resources

TIDA-050008	Design Folder
TPS3703-Q1	Product Folder
TPS3850-Q1	Product Folder
TPS3890-Q1	Product Folder
LM4132-Q1	Product Folder
TLV1805-Q1	Product Folder
LM73605-Q1	Product Folder
TPS62065-Q1	Product Folder
TPS61240-Q1	Product Folder
AutoCrankSim-EVM	Tool Folder

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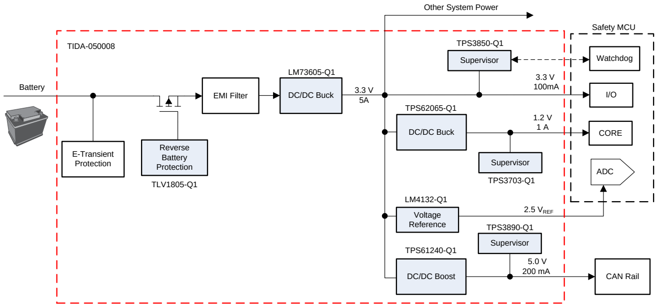
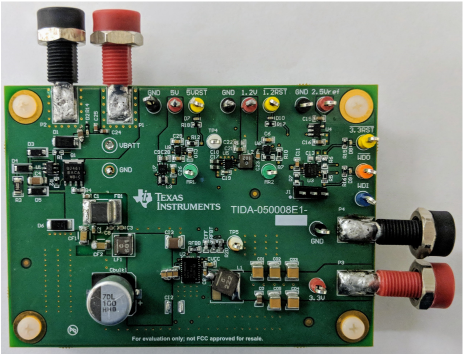
Features

- Accurate supervision (1% max, -40ºC to +125ºC) for overvoltage and under voltage monitoring
- Programable RESET delay for all supply rails
- Programmable window watchdog timer to interface with safety MCU
- Precision voltage reference for accurate ADC diagnostics and monitoring
- Power supply from automotive battery providing 5-V, 3.3-V, and 1.2-V rails
- 5-A Integrated, 2.2-MHz synchronous wide input voltage buck DC/DC converter
- Reverse battery protection with low voltage drop (~20 mV)
- Operating range 3.5 V to 24 V, supports wide range of battery voltage conditions up to 42 V transients
- Emissions tested according to CISPR 25 Class 5

Applications

- Front Camera
- Driver Monitoring Systems
- Mirror Replacement
- Front Long Range Radar
- ADAS Domain Controller





1 System Description

ADAS systems process and analyze data from local or remote sensor such as camera, radar, or lidar to either output video or use machine-vision algorithms to perceive the environment in and around the car. For systems that have to achieve higher levels of functional safety (for example systems that control steering or braking functions), an MCU for functional safety applications and precision voltage monitoring of the processor's supply rails (and other critical system rails) may be used. This design focuses on applications up to 15 W.

Figure 1 shows an example of a mono front camera system. Systems can vary in number of sensors and cameras depending on the application.

Figure 1. Example of Mono Front Camera Block Diagram

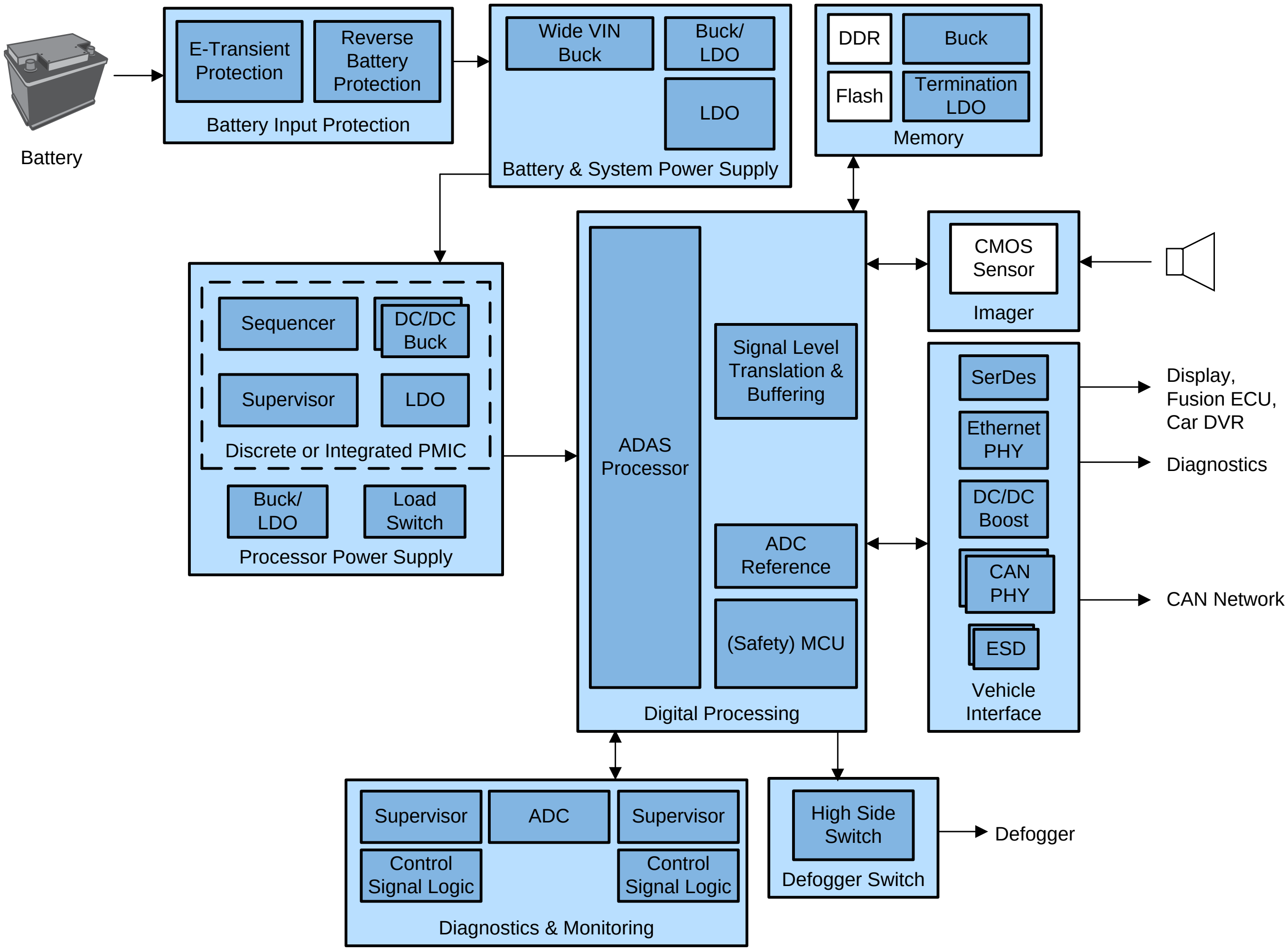
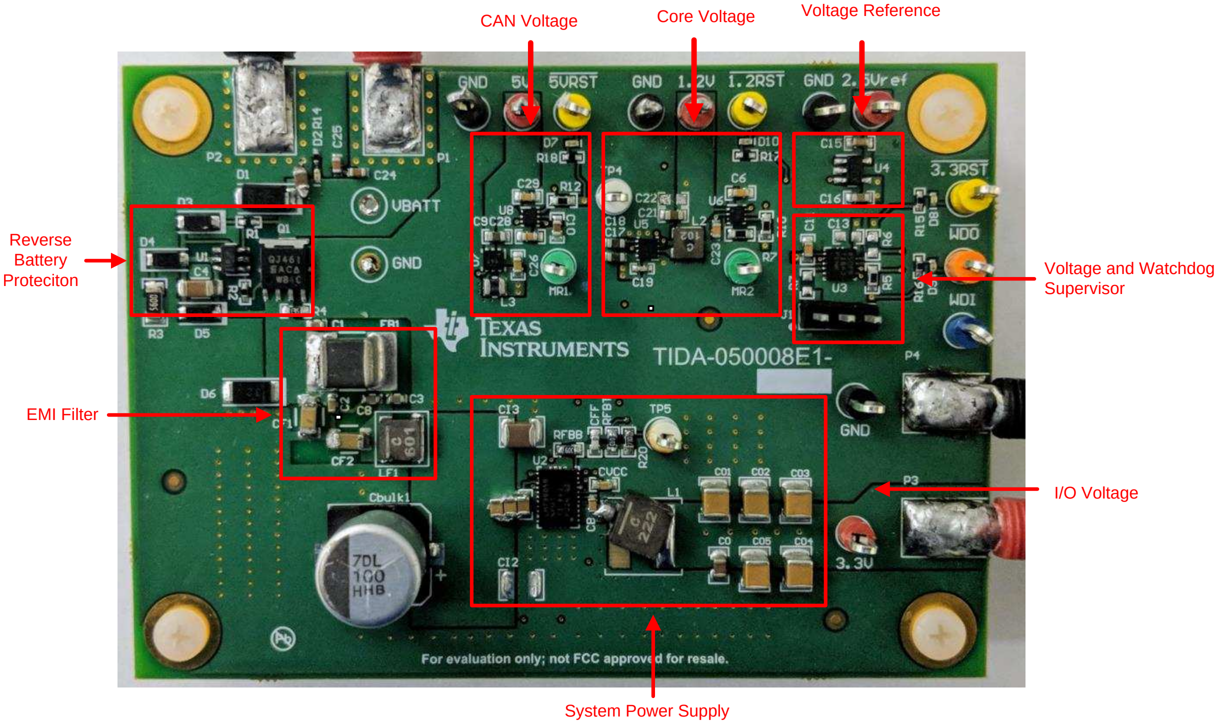


Figure 2 shows each subsystem and block on the actual TIDA-050008 board. The red blocks are all components located on the TIDA-050008 board and cover the power requirements for a typical safety MCU and CAN PHY. Functionality such as voltage supervision and watchdog timing are done with supervisor ICs. They provide features such as overvoltage and undervoltage monitoring, manual reset, programmable RESET delays, and programmable window watchdog timers.

Figure 2. TIDA-050008 Subsystems Highlight



1.1 Key System Specifications

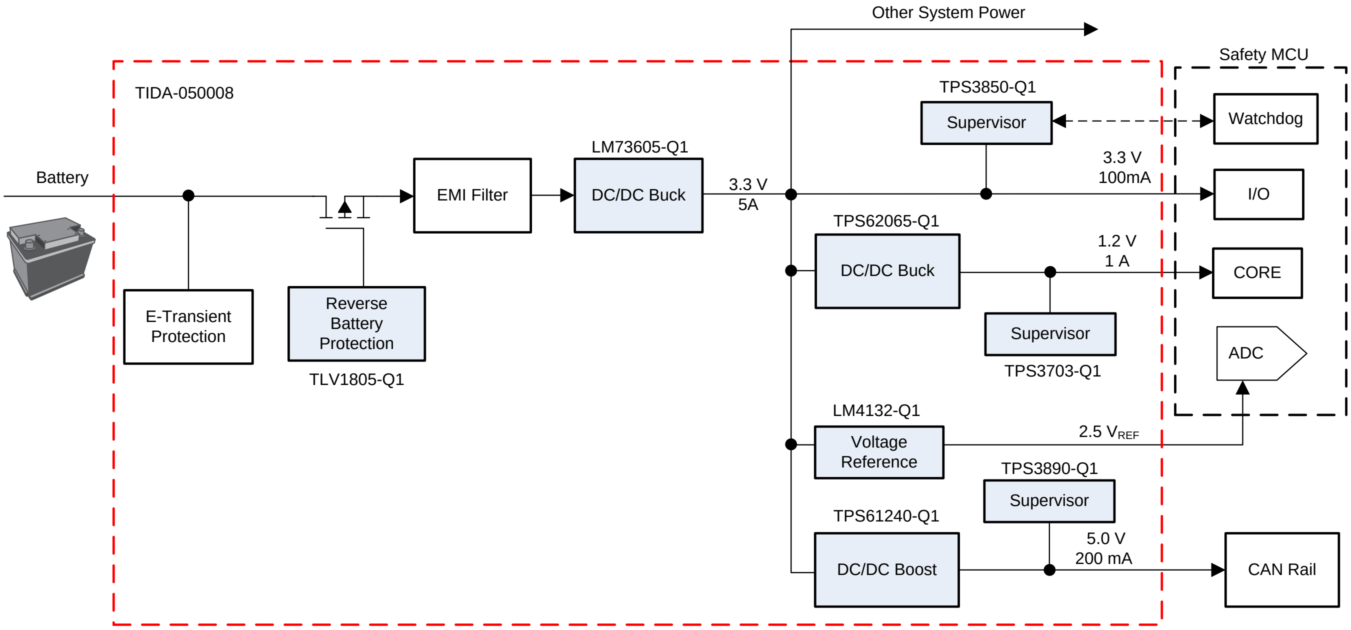
Table 1. Key System Specifications

PARAMETER		COMMENTS	MIN	TYP	MAX	UNIT
SYSTEM INPUT						
V_{IN}	Input voltage	Battery voltage range (DC)	3.5	13.5	24	V
V_{SYS}	System supply output voltage		—	3.3	—	V
I_{SYS}	System supply output current		—	—	5	A
V_{CORE}	Core-voltage supply output voltage	—	—	1.2	—	V
I_{CORE}	Core-voltage supply output current	—	—	—	1	A
$V_{I/O}$	I/O supply voltage	—	—	3.3	—	V
$I_{I/O}$	I/O supply output current	—	—	—	0.1	A
V_{CAN}	CAN supply voltage	—	—	5.0	—	V
I_{CAN}	CAN supply output current	—	—	—	0.2	A
V_{REF}	ADC Voltage Reference	—	—	2.5	—	V
F_{SYS_SW}	Switching frequency	Switching frequency of all supplies in system	2.2	—	3.5	MHz
V_{IT}	Voltage Supervisor Error	Error of threshold voltage in undervoltage and overvoltage conditions	—	—	1	%

2 System Overview

2.1 Block Diagram

Figure 3. TIDA-050008 Functional Block Diagram



2.2 Design Consideration

This design has been created with the following considerations in mind:

- Precision voltage supervision for processor rails and watchdog monitoring for the MCU
- Provide precision voltage reference for voltage monitoring and diagnostics ADC
- Provide system supply currents up to 5 A at 3.3 V.
- Minimize electromagnetic interference (EMI) and solution size.
- Reduce conducted emissions below CISPR 25 Class 5 conducted emissions limits
- Withstand reverse battery condition
- Operate through start-stop and cold-crank down to 3.5 V
- Optimize the individual blocks for smallest possible solution size
- Provide power for CAN PHY and Safety MCU

2.3 Highlighted Products

This reference design uses the following TI products:

- TLV1805-Q1: 40 V Push-pull Comparator for reverse battery protection. This is a low voltage drop alternative to discrete diodes.
- LM73605-Q1: 5-A synchronous buck converter with a wide input voltage range from 3.5 V to 36 V (42-V transients), enabling the device to work directly from an automotive battery.
- TPS62065-Q1: Highly-efficient 3-MHz synchronous buck converter. Has power-save mode operation at light load conditions to maintain high efficiency over load current ranges.
- TPS61240-Q1: Fixed 5 V output 3.5-MHz boost converter. TPS61240-Q1 allows the use of small inductor and capacitors to achieve a small solution size.
- TPS3850-Q1: Precision voltage supervisor with under and voltage monitoring. The TPS3850-Q1 doubles as a programmable window watchdog timer.
- TPS3703-Q1: Small form factor precision window supervisor. Does not require any external resistors for setting overvoltage and undervoltage thresholds, which further increases overall accuracy and reduces solution size and cost.
- TPS3890-Q1: Low-quiescent current precision voltage supervisor. Available in a small 1.5-mm × 1.5-mm package, making the device well-suited for space constrained applications
- LM4132-Q1: Precision series voltage reference. This device has 0.05% output initial voltage accuracy and a low temperature coefficient of 10 ppm/ºC.

The following subsections detail each device and explain their selection for this application.

2.3.1 TLV1805-Q1

The TLV1805-Q1 is a comparator that is used to sense the battery voltage for reverse battery conditions. The unique combination of wide supply range, push-pull output, rail-to-rail inputs, low quiescent current, and fast output response makes this device an easy choice for reverse battery applications.

2.3.2 LM73605-Q1

The LM73605-Q1 is the main system supply in this reference design. The wide input voltage range, high integration, and fast switching at 5-A make this device a top choice for the wide input, voltage power front end. The switching frequency of the device is adjustable between 350 kHz to 2.2 MHz. The switching frequency is selected to be 2.2 MHz because there should be minimal interference in the AM band (530 kHz to 1.8 MHz) for automotive applications. The benefit to switching above the AM band rather than below is that the faster switching frequency reduces the physical size of the output inductor and decreases the total solution size.

Though not used in this reference design, this switcher supports external clock synchronization to avoid beat frequencies between multiple converters or to allow a master to dither the clock signal. This feature can be very useful for optimizing systems for EMI performance.

2.3.3 TPS62065-Q1

The TPS62065-Q1 provides 1.2 V for the core voltage supply of a typical MCU in this design. Its high efficiency and 2-A current capibilties makes it a great fit to provide the core supply. The switching frequency is a fixed 3-MHz to provide minimal interference to the AM band. The TPS62065-Q1 is optimized for operation with a tiny 1-µH inductor and a small output capacitor to achieve smallest solution size and high regulation performance.

2.3.4 TPS61240-Q1

The TPS61240-Q1 is 3.5-MHz boost converter. Its fixed 5 V output lowers the amount of external components required for low cost, low size solutions. The device has 450 mA output current capibilties to support single or dual CAN transceivers at 200-mA maximum current each. During light load conditions the device will automatically pulse skip allowing maximum efficiency.

2.3.5 TPS3850-Q1

The TPS3850-Q1 is a voltage supervisor that achieves 0.8% accuracy maximum across operating temperature. The overvoltage and undervoltage monitoring and built-in window watchdog timer makes this device an easy choice to monitor the I/O voltage rail of the MCU and provide watchdog diagnostic for the MCU as well. The device comes in set threshold for overvoltage and undervoltage monitoring so external resistors are not required. The TPS3850-Q1 has user-programmable reset delay and window watchdog timeouts.

2.3.6 TPS3703-Q1

The TPS3703-Q1 is a small-sized precision window voltage supervisor. Like the TPS3850-Q1, this device has integrated overvoltage and undervoltage monitoring with set thresholds and tolerances. With many fixed options, the TPS3703-Q1 does not require many external components which can reduce solution size and BOM cost. Because of its high performance and features, the TPS3703-Q1 is perfect to provide supervision to the main core rail of the MCU while keeping a small board footprint.

2.3.7 TPS3890-Q1

The TPS3890-Q1 is a low-quiescent current, under voltage supervisor. Similar to the TPS3703-Q1, the TPS3890-Q1 comes in a fixed voltage version and small WSON 1.5-mm × 1.5-mm package which makes it capable in size constrained applications. The device has adjustable reset delays for proper sequencing in multi-rail systems such as ADAS applications.

2.3.8 LM4132-Q1

The LM4132-Q1 is a family automotive grade precision voltage reference. Available in multiple fixed voltage options and accuracy grades, the LM4132-Q1 provides great flexibility and performance. For systems that require voltage monitoring more than the ones this design covers, a precision voltage reference is critical for an ADC to provide accurate diagnostic.

2.4 System Design Theory

2.4.1 Printed-Circuit Board (PCB) and Form Factor

This design does not have any specific requirements for the board shape or size. The main objective is to have as small of a solution size as possible for each power supply sub-system. Figure 4 shows a three-dimensional (3-D) rendering of the PCB, followed by a labeled photograph of the actual board in Figure 5.

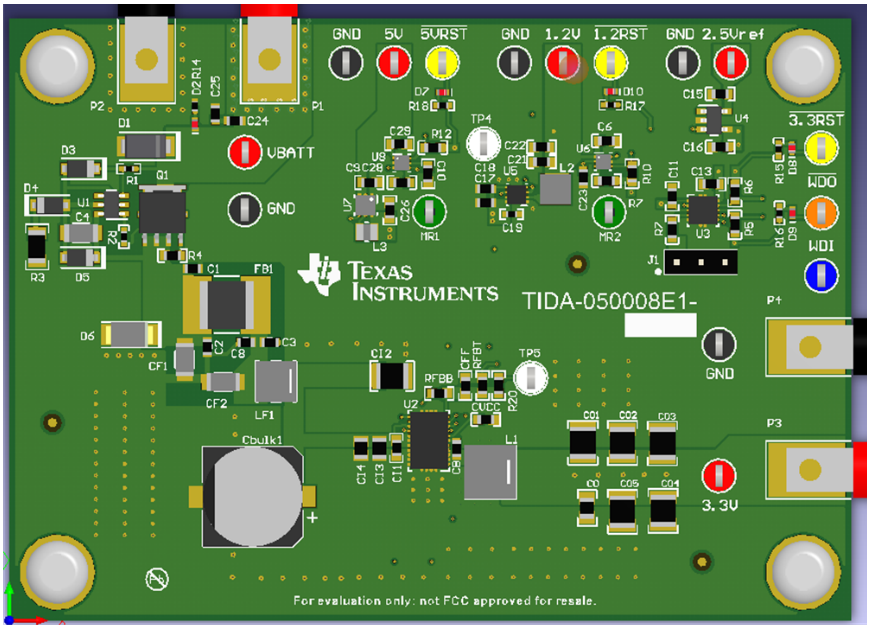


Figure 4. TIDA-050008 PCB Render

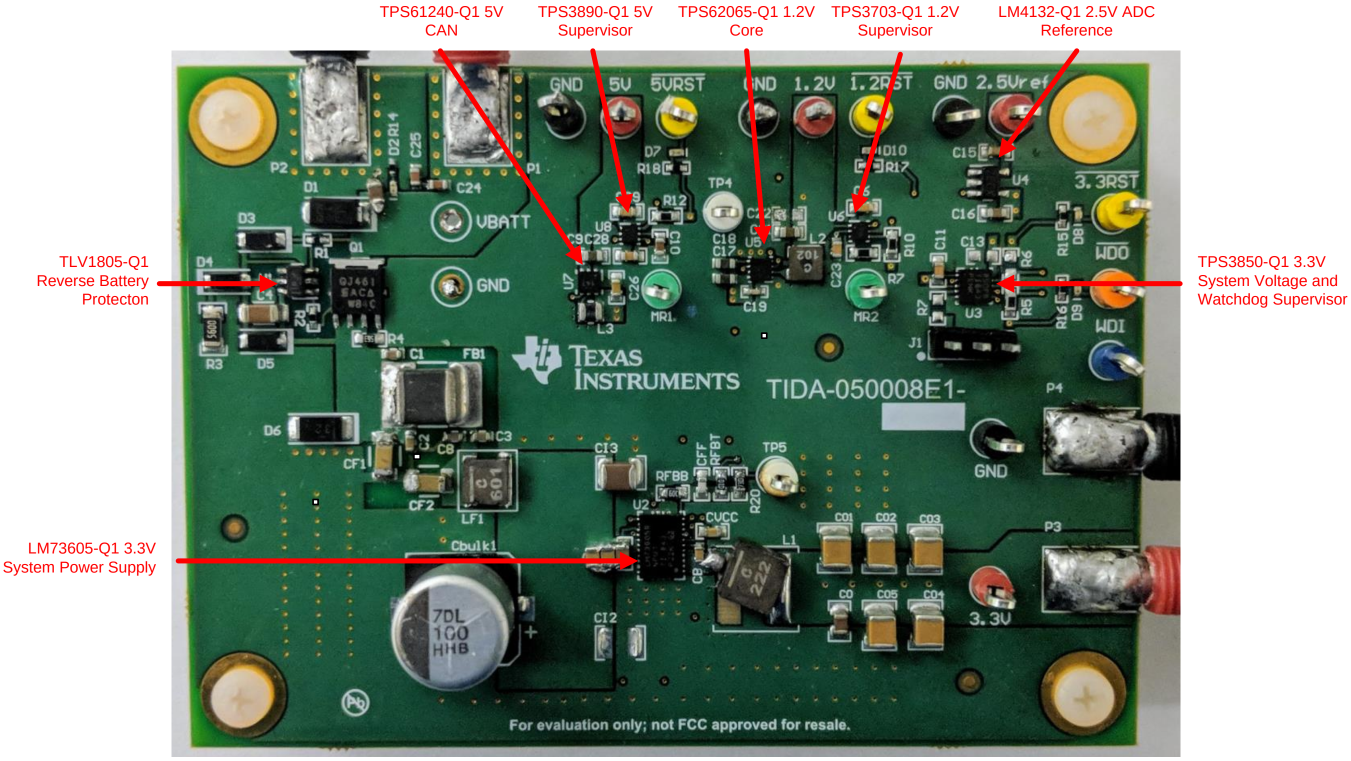


Figure 5. TIDA-050008 Labeled Supplies and Components

2.4.2 Input Protection and Wide-V_{IN} DC-DC

2.4.2.1 TVS Diodes

Transient voltage suppression (TVS) diodes are required on the supply input of the system to protect against both positive and negative going transients. The transients of concern are detailed in ISO 7637-2:2004, pulses 1 and 2a. Many systems in a car can simply shut down during these transients until the condition passes; alternatively, many ADAS applications require continuous operation. For this reason, the transients must be shunted instead of using an over voltage shutdown scheme.

Figure 6 shows a schematic of the input transient protection.

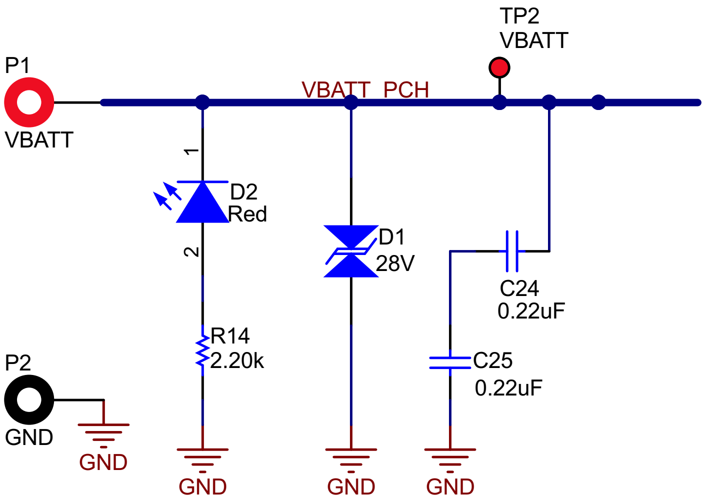


Figure 6. Input Transient Protection

The diode breakdown voltages have been chosen such that transients are clamped at voltages that protect the MOSFET and the rest of the system. The positive clamping device must clamp above a double-battery (jump-start) and clamped load dump voltages, but lower than the maximum operating voltage of the downstream devices. In this case, the requirement is to clamp around 28 V but have a maximum clamping voltage below 40 V. Ideally, the best choice is to specify 36 V as the approximate maximum clamping voltage. The reverse clamping device must clamp negative voltages greater than the battery voltage so that it does not short out during a reverse-battery condition.

The two series capacitors should be mounted at right angles to each other. Placing ceramic SMT capacitors in series-angle is common practice in automotive applications. The most common failure modes for ceramic SMT capacitors is a short or open. The series connection is for if one of the capacitors short-out it will not short the bus and the other capacitor will still be functional. The right-angle reason is so that if the board flexes and damages one of the capacitors, the other capacitor should survive since it was at the opposite angle. The capacitors should also be closest to the input connectors since they will be handling the high voltage, high frequency transients. The current path needs to be as short as possible between the jacks.

2.4.2.2 Reverse Battery Protection

Reverse battery protection is a requirement for nearly every electronic module in a vehicle, both by original equipment manufacturer (OEM) standards as well as ISO 16750-2, an international standard that pertains to supply quality. The TLV1805-Q1 circuitry has been subjected to selected ISO 16750-2 and ISO 6737-2 waveforms for 12 V systems. The circuits survived with no performance degradation, and the load voltage did not exceed design limits. The circuit was tested on an evaluation module and does not imply full ISO certification of the board, or that the use of these circuits implies ISO certification of users end equipment. For more information, check the TLV1805-Q1 product page and datasheet.

Figure 7 shows a schematic of the reverse battery input protection.

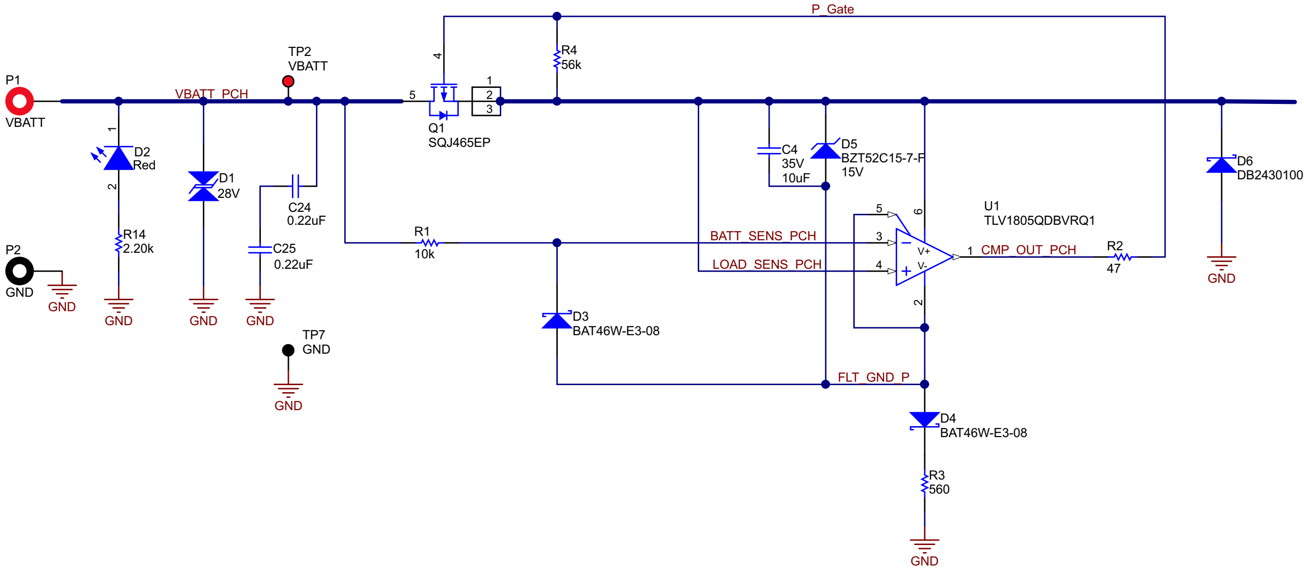


Figure 7. Reverse Battery Input Protection

This implementation of reverse battery protection uses a P-channel MOSFET controlled by the TLV1805-Q1 device. The TLV1805-Q1 is a low-power comparator that is used to sense the voltage between the P-FET. In reverse battery conditions, the TLV1805 will disable the FET to protect the devices on the board. The power dissipation of a traditional diode rectifier solution is significantly higher due to the typical 600-mV to 700-mV forward drop. A very-low forward voltage drop can be achieved using low $R_{DS(ON)}$ external P-channel MOSFETs. This low forward voltage drop from the supply to the system yields much higher efficiency, less heat, and a lower input voltage operating range while protecting the system from a reverse polarity condition.

The FET must have a rating which is at least as high as the clamped input voltage. This reference design uses a -60-V, -30A P-FET with a -2-V gate-source threshold voltage.

2.4.2.3 Input EMI Filter

The schematic in Figure 8 shows the EMI filter at the system supply input, after the reverse battery protection.

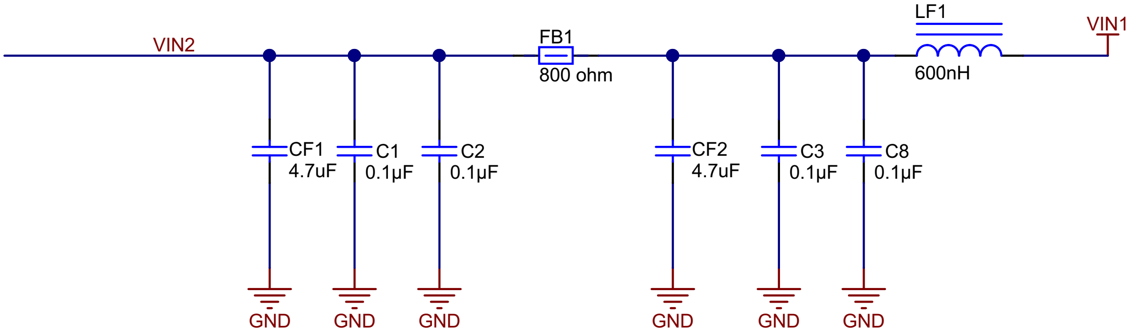


Figure 8. Input EMI Filter Schematic

The switching frequency of the system power supply is 2.2 MHz. The EMI filter inductor requirement can be eased since filtering out frequencies below the AM band typically requires larger inductors with more inductance, usually 10 µH or more, as more inductance provides more impedance at lower frequencies. Decoupling capacitors C3 and C8 filter out the high-frequency noise that the inductor LF1 cannot attenuate.

The ferrite bead FB1 has a higher resonant frequency than inductor LF1, around 100 MHz. The impedance due to the higher resonant frequency attenuates any unfiltered noise around this 100-MHz band that has been conducted upstream from the LF1-CF2 node to VIN2 and acts as a high-frequency current choke by increasing the impedance for higher-frequency currents from the larger upstream loop, from VIN2 to downstream components after VIN1. Similar to capacitors C3 and C8 after LF1, the decoupling capacitors C1 and C2 provide a low impedance path for high-frequency currents to ground.

When selecting and adding decoupling capacitors, it may seem attractive to simply add more capacitors. No matter how much decoupling is used, designers must take careful consideration to avoid parallel resonances resulting from the unseen parasitics of the passives. Parallel resonances can cause EMI problems that may be difficult to pinpoint and address.

While it is critical to select the right components for the EMI filter, strategically laying out these components is equally critical for an effective EMI filter.

2.4.2.4 Wide Input Voltage Buck Converter

The LM73605-Q1 is an AEC-Q100 qualified, wide-input voltage buck regulator used as a front-end supply to provide a 3.3-V system voltage and I/O voltage of the MCU. With a nominal input voltage range of 3.5 V to 36 V and transients up to 42 V, the device can continue operation through most battery conditions such as start-stop, cold-crank, and load dump.

Figure 9 shows a schematic of the wide input voltage buck.

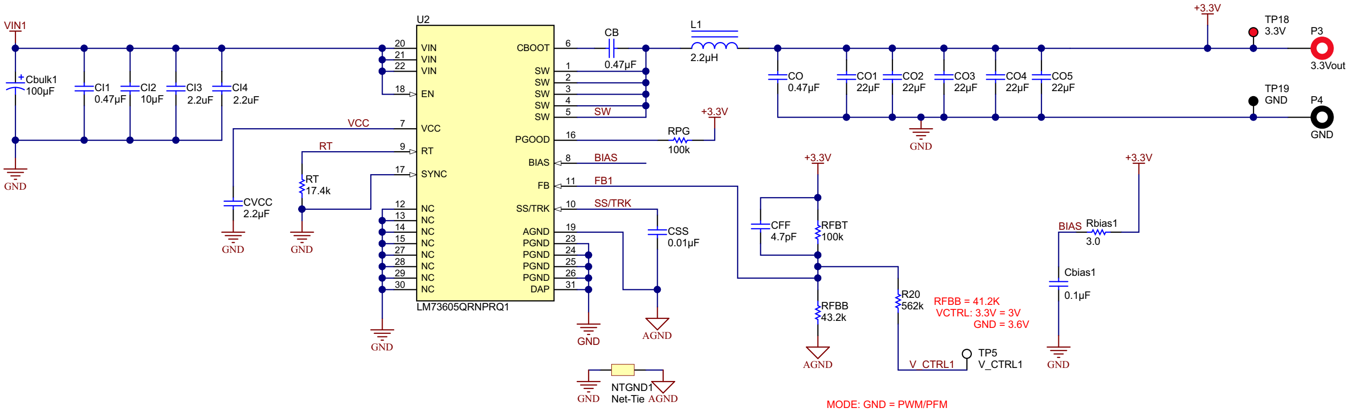


Figure 9. Wide Input Voltage Buck

The LM73605-Q1 delivers 5 A and configures for a 2.2-MHz switching frequency and a light load architecture (PFM), which means that the device lowers its switching frequency for lower current loads. V_CTRL1 is used to apply voltage to the FB to test overvoltage and undervoltage conditions.

2.4.3 Power Supply Design Considerations

For this power supply, choose inductors such that:

- The ripple current is between 20% to 40% of the load current I_{LOAD} with the given switching frequency, input voltage, and output voltage. This reference design uses 40%.
- The temperature ratings are appropriate for automotive applications, typically –40°C to 125°C for ADAS applications.
- Saturation current is chosen per Equation 1 for peak current, plus additional margin.

$$I_{SAT} \left(I_{LOAD} + 0.5 \times I_{RIPPLE} \right) \times 1.2 \qquad (1)$$

An important recommendation for ADAS applications is selecting ceramic capacitors that use X7R dielectric material, which ensures minimum capacitance variation over the full temperature range. The voltage rating of the capacitors must be greater than the maximum voltage and twice the typical voltage across its terminals to avoid DC bias effects. The amount of output capacitance used depends on output ripple and transient response requirements, for which there are many equations and tools available online to help estimate. The supplies in this solution have been designed for a ±2.5% total transient response. Low equivalent series resistance (ESR) ceramic capacitors have been used exclusively for the purpose of reducing ripple. For internally-compensated supplies, see the device-specific data sheets, as they may have limitations on acceptable LC output filter values.

ICs must always be qualified per AECQ100. TI parts that are qualified typically have part numbers ending in "-Q1".

For improved accuracy, all feedback resistor dividers must use components with 1% tolerance.

2.4.3.1 TPS62065-Q1 Core-Voltage Supply

The TPS62065-Q1 is a 2-A, buck converter switching at a fixed 3-MHz. The TPS62065-Q1 is optimized for operation with a tiny 1-µH inductor and a small output capacitor to achieve smallest solution size and high regulation performance. This device also has the ability to operate in a power save mode to maintain efficiency in light-load conditions with pulse-frequency modulation (PFM). V_CTRL2 is used to apply voltage on the feedback to test overvoltage and undervoltage conditions.

Figure 10 shows the schematic for the device.

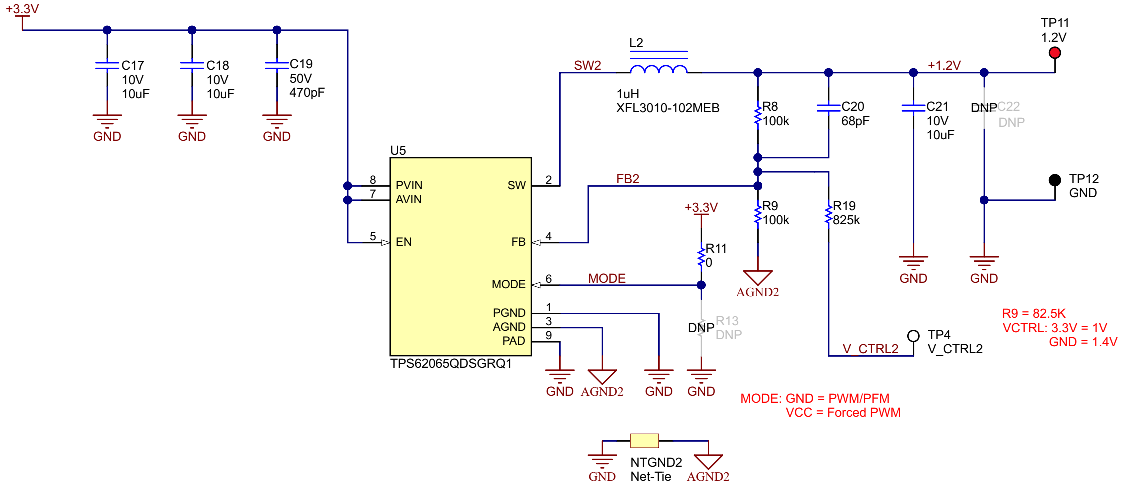


Figure 10. Core-Voltage Supply Schematic

2.4.3.2 TPS61240-Q1 CAN-Voltage Supply

The TPS61240-Q1 device provides the 5-V output voltage required for a CAN bus (see Figure 11). The TPS61240-Q1 is a fixed 5V, 3.5-MHz boost converter that requires minimal external components for low cost and size solutions. The device has 450 mA output current capibilties to support single or dual CAN transceivers at 200-mA maximum current each. During light load conditions the device will automatically pulse skip to achieve maximum efficiency.

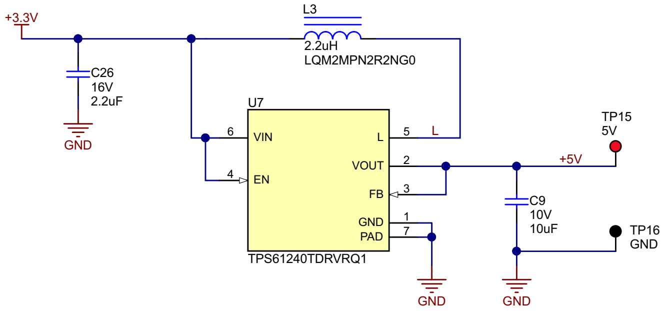


Figure 11. 5-V CAN Supply Schematic

2.4.4 Watchdog, Voltage Supervision, and Reference

Diagnostics and monitoring subsystems play a key role in ADAS systems. In this reference design, each supply voltage is monitored by a dedicated voltage supervisor with different features and specifications to meet the requirements. Features such as watchdog monitoring, window voltage supervision, and programmable reset delays allows for multiple layers of security that can help customers achieve their functional safety goals. Over-voltage monitoring is required for processor applications because high temperatures may affect DC-DC converters nominal values. This may cause the output voltage to drift higher than a processor's tight voltage tolerance. A series voltage reference is also added to provide precision reference to an ADC (internal or external) for accurate diagnostics and monitoring in case other system rails or sensors need to be monitored.

2.4.5 TPS3850-Q1 Watchdog and System-Voltage Monitoring

The TPS3850-Q1 combines a precision voltage supervisor with a precision programmable window watchdog timer. The TPS3850-Q1 window comparator achieves 0.8% accuracy (–40°C to +125°C) for both overvoltage and undervoltage thresholds. This device is an easy choice to monitor the I/O voltage rail of the MCU and provide watchdog diagnostic for the MCU as well. The programmability of the TPS3850-Q1 allows adjustable reset delay and window watchdog timeouts, watchdog ratios, and watchdog disable. $\overline{\text{RESET}}$ and $\overline{\text{WDO}}$ are open-drain outputs that require pull-up resistors to a logic-high voltage. An LED is added in parallel for physical indications of a reset occurring. Figure 12 shows the schematic of the TPS3850-Q1 voltage and watchdog monitoring design. The variant of the TPS3850-Q1 in this design is a 7% tolerance, 3.3 V threshold monitor.

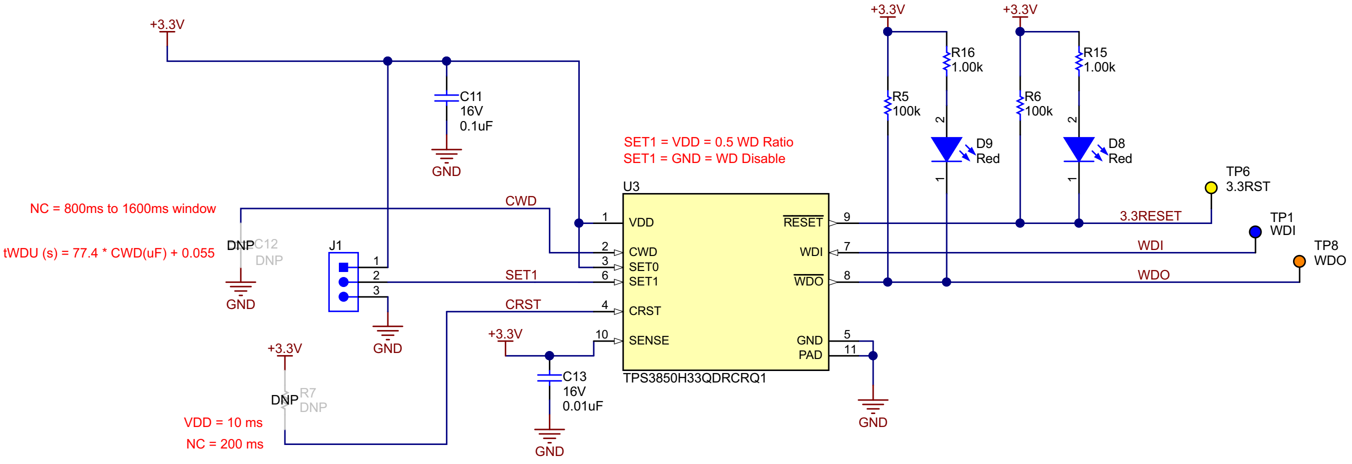


Figure 12. System-Voltage and Watchdog Monitoring Schematic

2.4.6 TPS3703-Q1 Core-Voltage Window Monitoring

The TPS3703-Q1 is a 6-pin WSON precision window voltage supervisor for overvoltage and undervoltage monitoring. TPS3703-Q1 requires minimum passive components because of its various one-time programmable options. The TPS3703-Q1 has 50 mV threshold steps from 500 mV to 1.3V with popular voltage options from 1.5 V to 5.0 V. Tolerances are available from 3% to 7% in 1% steps. Seven fixed time delay options with a programmable delay option with a capacitor. Combined with internal glitch immunity and latch feature, the TPS3703-Q1 is a perfect fit to provide voltage supervision to the core-voltage of the MCU. Figure 13 shows the schematic of the TPS3703-Q1 window voltage monitoring design. The variant of the TPS3703-Q1 in this design is a 4% tolerance, 1.2V threshold monitor with a fixed option of 10 ms or 200 ms reset delay.

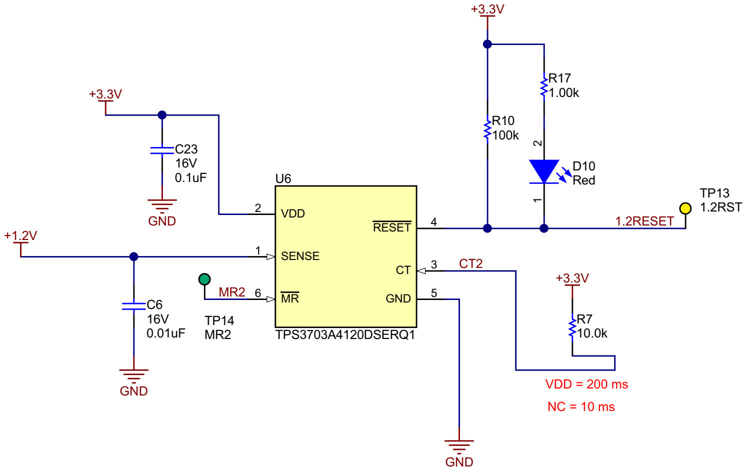


Figure 13. Core-Voltage Window Monitoring Schematic

2.4.7 TPS3890-Q1 CAN Undervoltage Monitoring

The TPS3890-Q1 is a low-quiescent current, under voltage supervisor. Similar to the TPS3703-Q1, the TPS3890-Q1 comes in small WSON 1.5-mm × 1.5-mm package and multiple fixed options in threshold voltage monitoring and tolerance options. The device provides programmable reset delays using an external capacitor. If window voltage monitoring is required for the CAN voltage rail, using the TPS3703-Q1 would be great replacement. Figure 14 shows the schematic of the TPS3890-Q1 undervoltage monitoring design. The variant of the TPS3890-Q1 in this design is a 7% tolerance, 5.0 V threshold monitor.

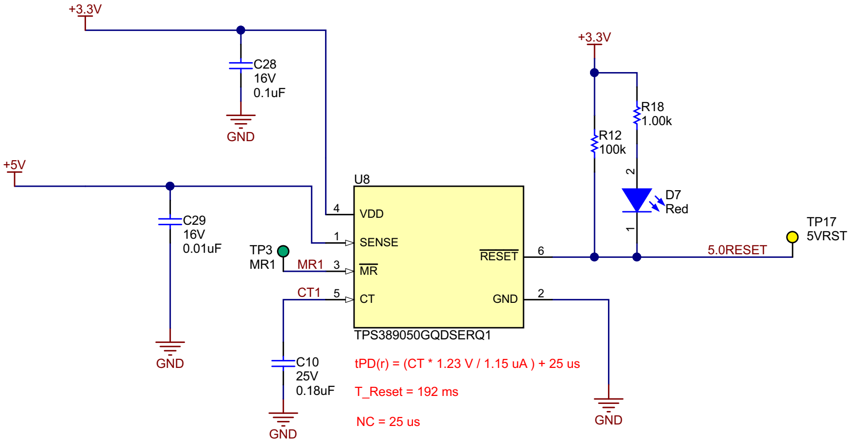


Figure 14. CAN Undervoltage Monitoring

2.4.8 LM4132-Q1 Precision ADC Reference

The LM4132-Q1 is a family of automotive grade precision voltage references. Available in multiple fixed voltage options and accuracy grades, the LM4132-Q1 provides flexibility and performance. With a maximum of 10 ppm/ºC temperature coefficient and 60 uA low-Iq, the LM4132-Q1 is a great fit for an ADC reference. For systems that require monitoring on other system voltages, a precision voltage reference is critical for an ADC to provide accurate diagnostic.

Figure 15 shows the schematic of the LM4132-Q1 precision ADC reference design. The variant of the LM4132-Q1 has initial output accuracy of 0.05% and 10 ppm/ºC temperature coefficient. Depending on the application's specifications and accuracy requirements, the LM4128-Q1 or REF34-Q1 may be a better fit for the ADC.

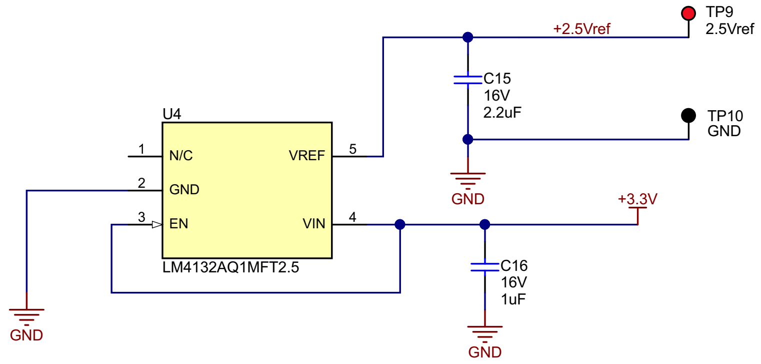


Figure 15. Precision ADC Reference Schematic

3 Hardware and Testing Requirements

3.1 Hardware

To get started with the TIDA-050008 board, simply connect the leads to the banana jack on the top-left corner of the board. The screw terminals are labeled VBATT and GND and color-coded red and black respectively to indicate the correct polarity of the supply (see Figure 16). The system voltage supply also has output terminals with banana jacks on the bottom-right corner of the board labeled 3.3V and GND. Connect a power supply that is capable of at least 13.5 V and 2 A to the leads to supply power.

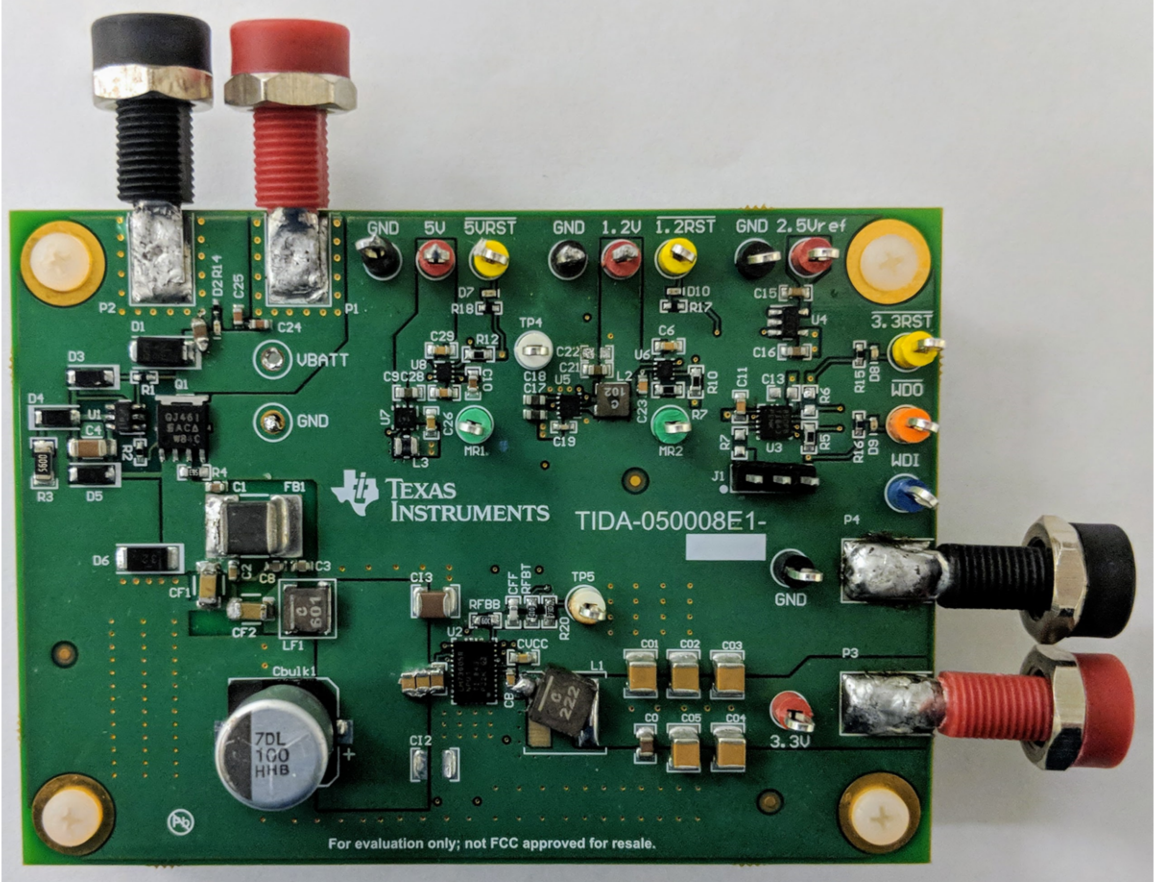


Figure 16. Board Input Terminals

3.2 Testing and Results

The following information shows how to set up for the various tests performed on this design.

To perform pulse testing, this design used the AutoCrankSim-EVM: Simulator for Automotive Cranking Pulses Evaluation Module Board. This board is available for purchase at: AUTOCRANKSIM_EVM: Simulator for Automotive Cranking Pulses Evaluation Module Board. If the designer wishes to build the board or simply view the design files, use the power design files from: PMP7233 Cranking Simulator Reference Design for Automotive Applications.

The following subsections show the test data from characterizing the switching power supplies, voltage supervisors, and voltage reference in the system.

3.2.1 Load Regulation and Efficiency

This section presents and discusses the 3.3V system-voltage supply load regulation and system-level power efficiency test results of the Wide-Vin LM73605-Q1 buck regulator. Figure 17 shows the output voltage variation of the 3.3-V system-voltage supply with varying load current, from no load to full load.

A close examination of Figure 17 shows low deviation from typical voltage supply across various loads. The input voltage is measured from the banana jack terminals, so there is a voltage drop from the reverse battery protection pass FET and EMI filter when it arrives to the LM73605-Q1. At full load, the device does not regulate well at 3.50 V input voltage due to the forward voltages and dropout voltage of the device.

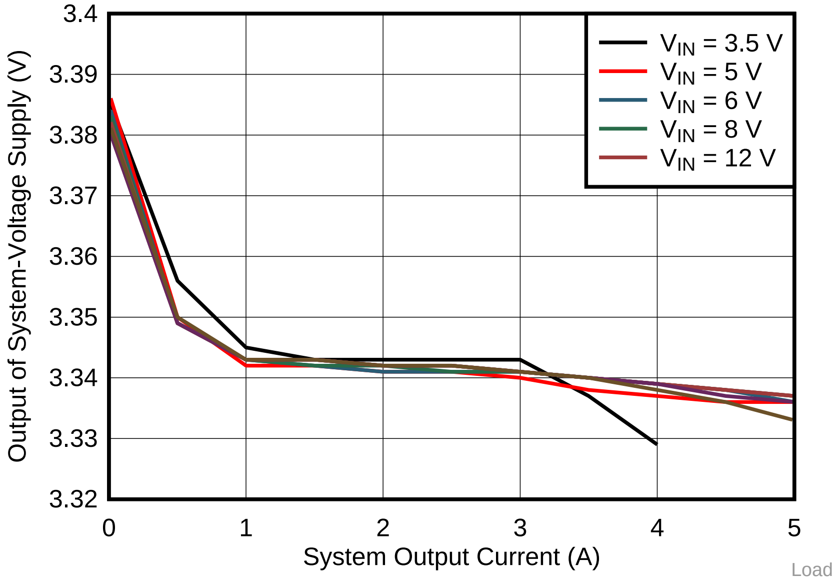


Figure 17. Load Regulation of 3.3V System-Voltage Supply

The following Figure 18 shows the efficiency of the system-voltage supply that supports a 15 W design. The system supply consists of the LM73605-Q1 supplying power to the rest of the system outside of TIDA-050008 at a max load of 5A at 3.3 V output. Output voltage and current measurements were taken across an input voltage range of 3.5 V to 24 V.

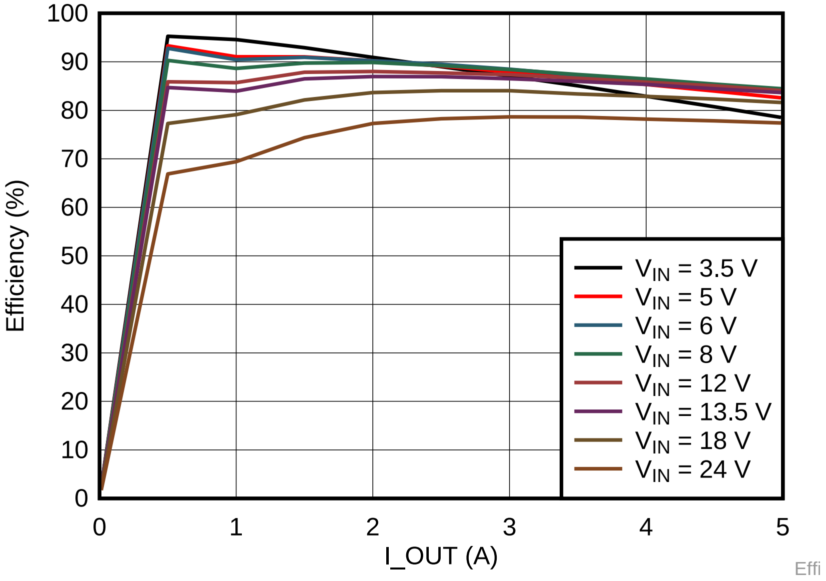


Figure 18. LM73605-Q1 3.3 V System-level Efficiency

Figure 19 shows the efficiency with varying input voltage and the full 5-A load. As expected, the measured peak efficiency appears to be around 8 V, with the efficiency dropping off as the input voltage increases.

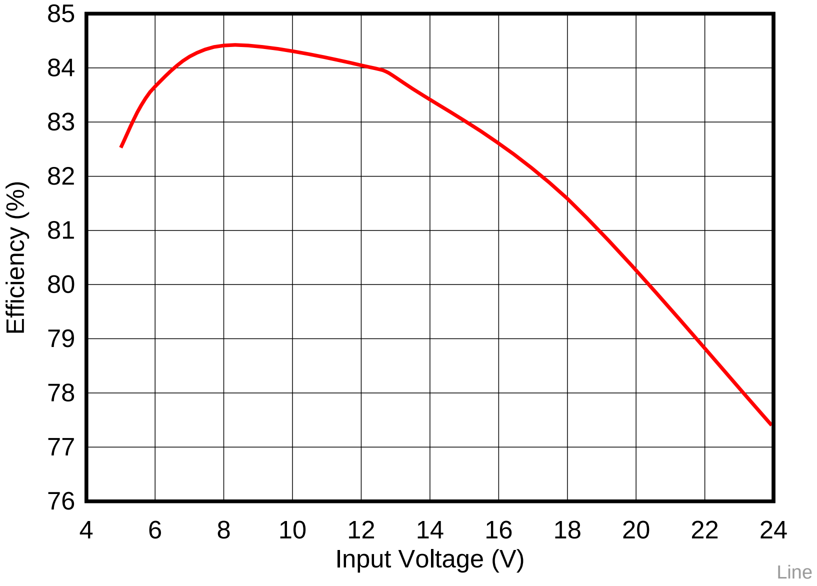


Figure 19. Full Load Efficiency for Varying Input Voltage

3.2.2 Switch Node Waveforms and Output Voltage Ripple

The following oscilloscope waveforms show the switch nodes and output voltage ripples of the various power supplies in the reference design. They are measured using the tip and barrel method. The switch nodes are measured from the SW pin to the power ground of the DC-DC converter. Output voltage ripple are measured closely between the output capacitor. Figure 20 and shows the switch node and output voltage ripple at the full load of the LM73605-Q1 buck converter. Channel 1 (blue) shows the switch node waveform and channel 2 (red) shows the output voltage ripple. The output voltage ripple measurements are AC coupled.

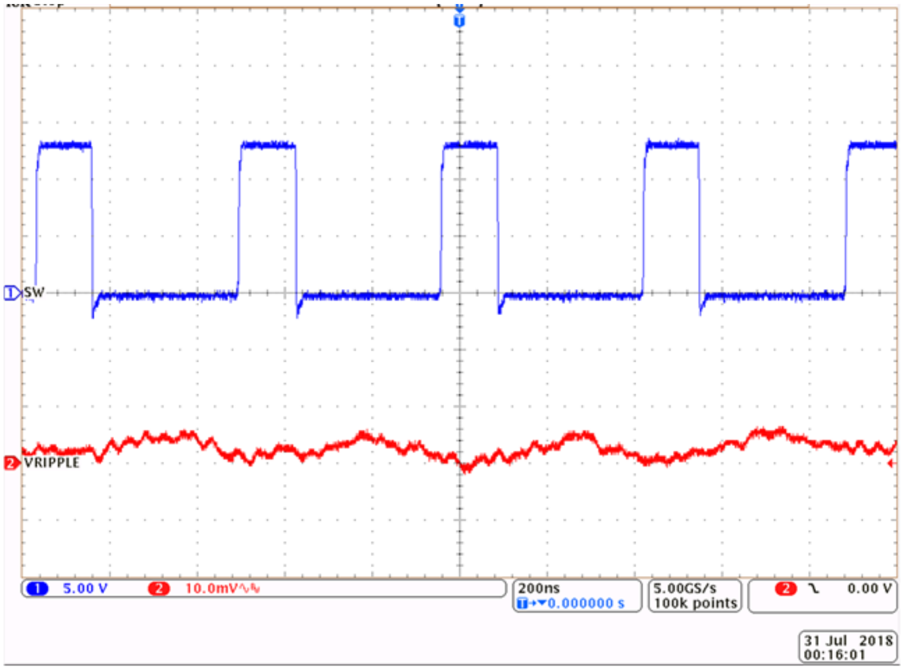


Figure 20. LM73605-Q1 Switch Node and Output Voltage Ripple, 13.5-V Input at 5-A Full Load

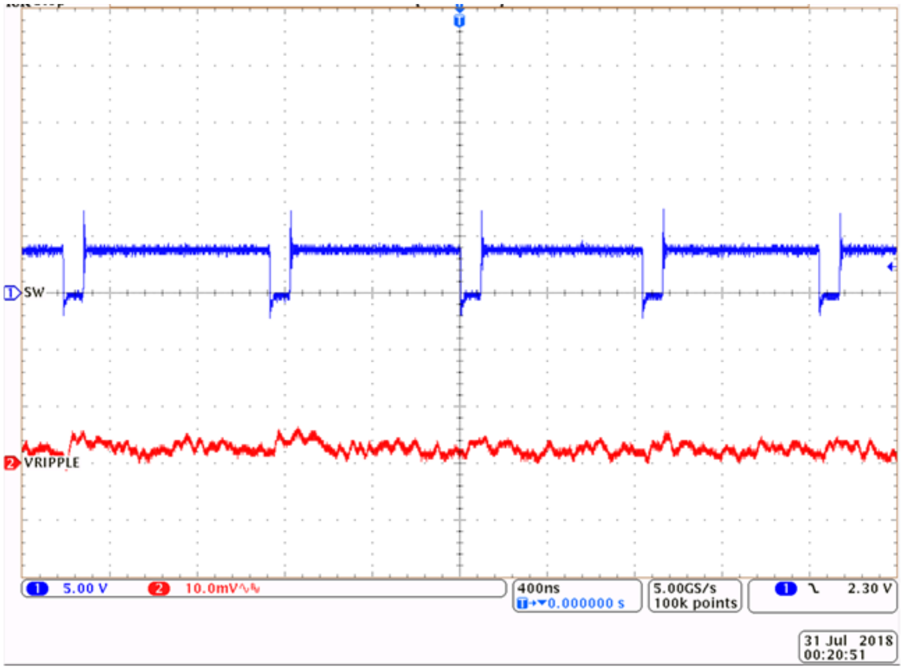


Figure 21. LM73605-Q1 Switch Node and Output Voltage Ripple, 4.5-V Input at 5-A Full Load

Figure 22 and Figure 23 show the switch node and output voltage ripple for the core-voltage and CAN-voltage supply. The first scope shot shows the TPS62065-Q1 1.2-V output, followed by the TPS61240-Q1 5-V output. This is with a 13.5 V input voltage and full load specifications.

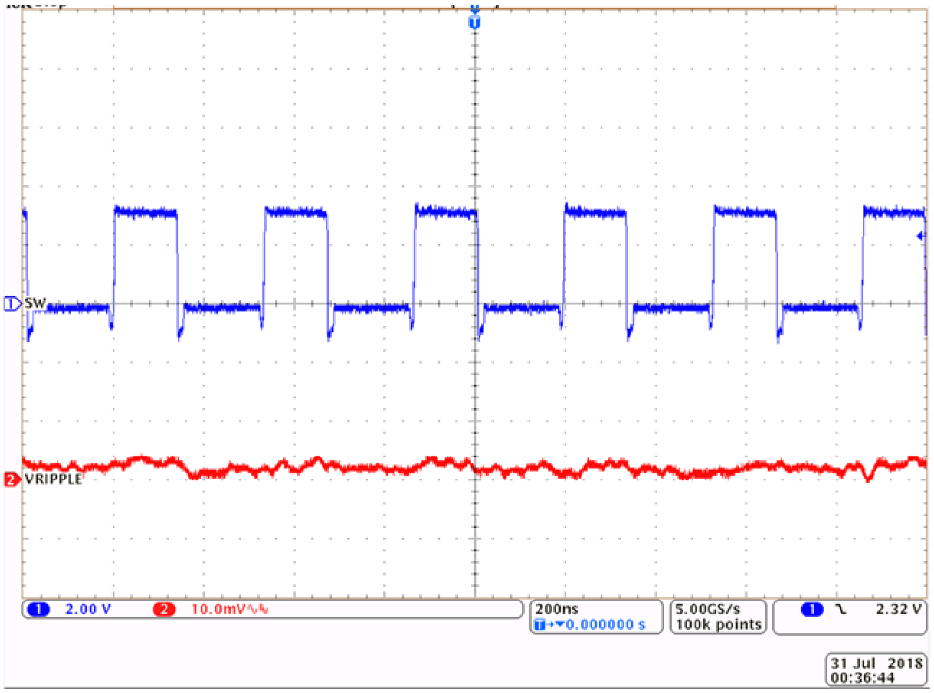


Figure 22. TPS62065-Q1 Switch Node and Output Voltage Ripple, 1.2-V Output at 1-A Full Load

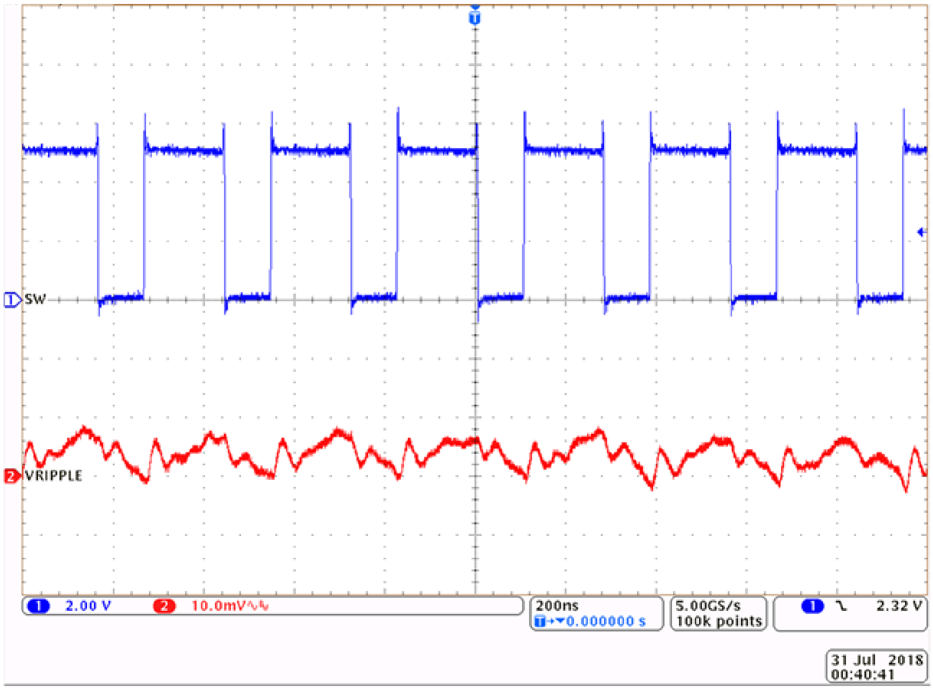


Figure 23. TPS61240-Q1 Switch Node and Output Voltage Ripple, 5.0-V Output at 200-mA Full Load

3.2.3 Load Transients

Figure 24 through Figure 27 shows the transient responses for system and core supplies. Channel 2 (pink) measures the AC-coupled output voltage and channel 4 (green) measures the current of the load transient

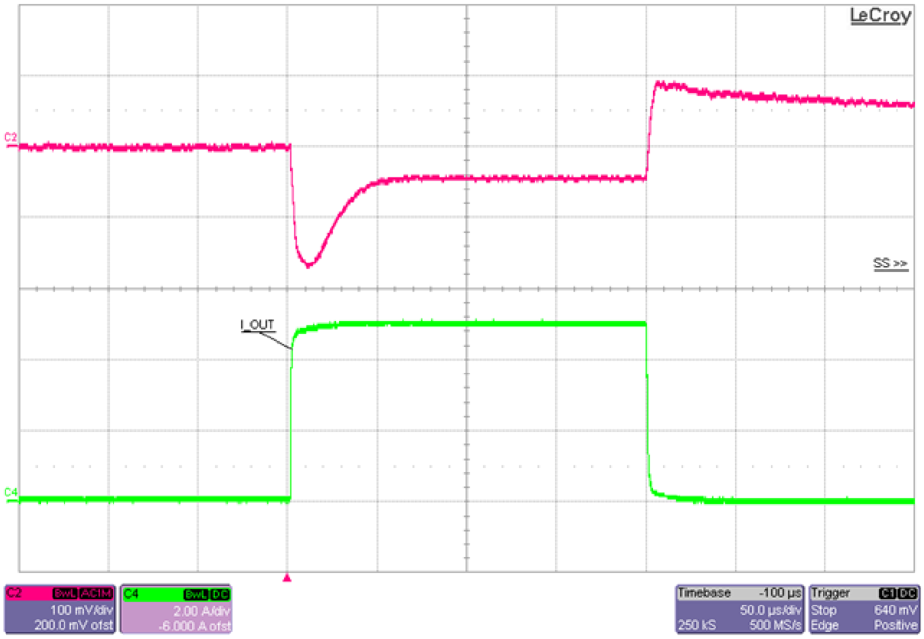


Figure 24. LM73605-Q1 0-100%, 0 A - 5 A Load Transient

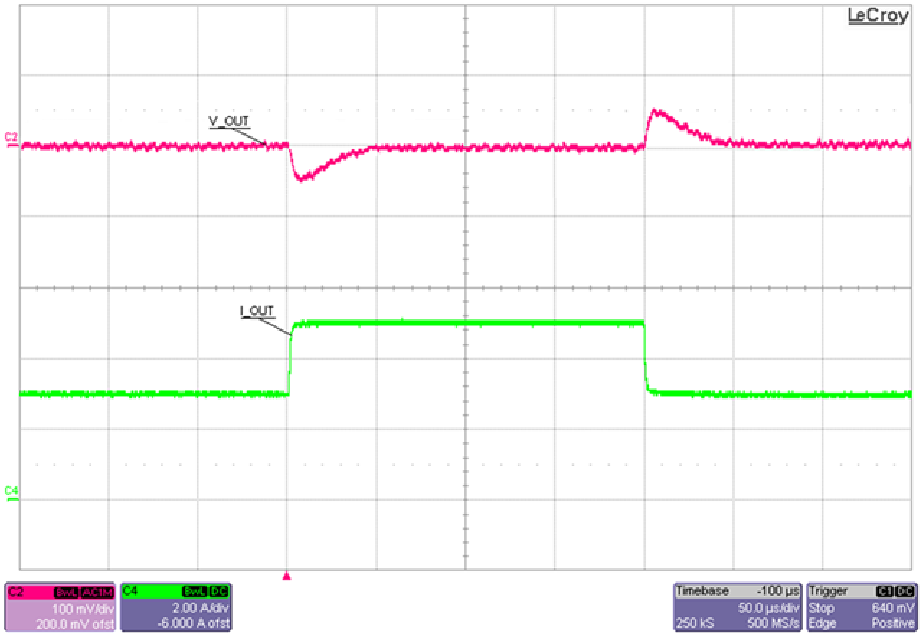


Figure 25. LM73605-Q1 50-100%, 2.5 A - 5 A Load Transient

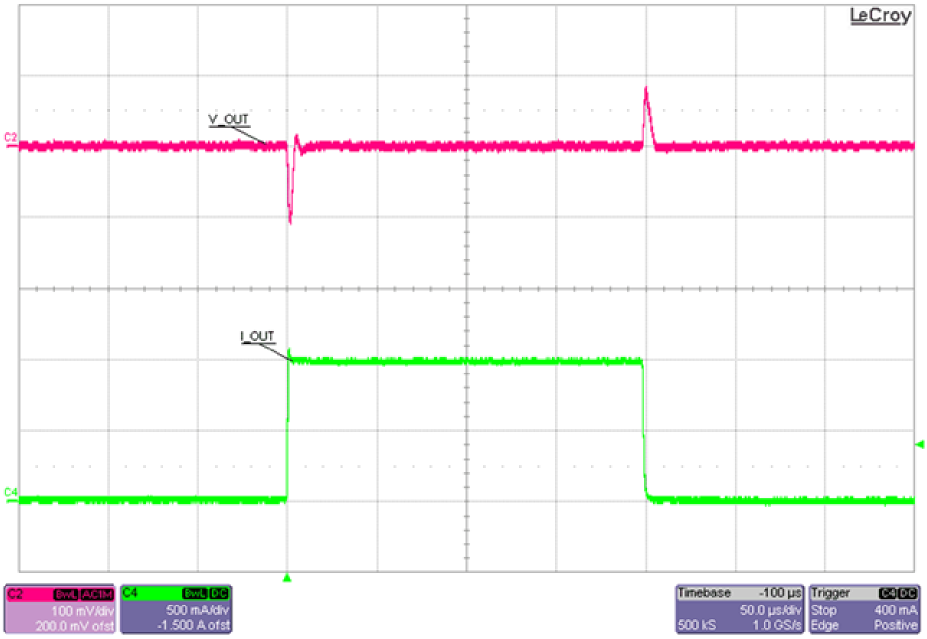


Figure 26. TPS62065-Q1 0-100%, 0 A - 1 A Load Transient

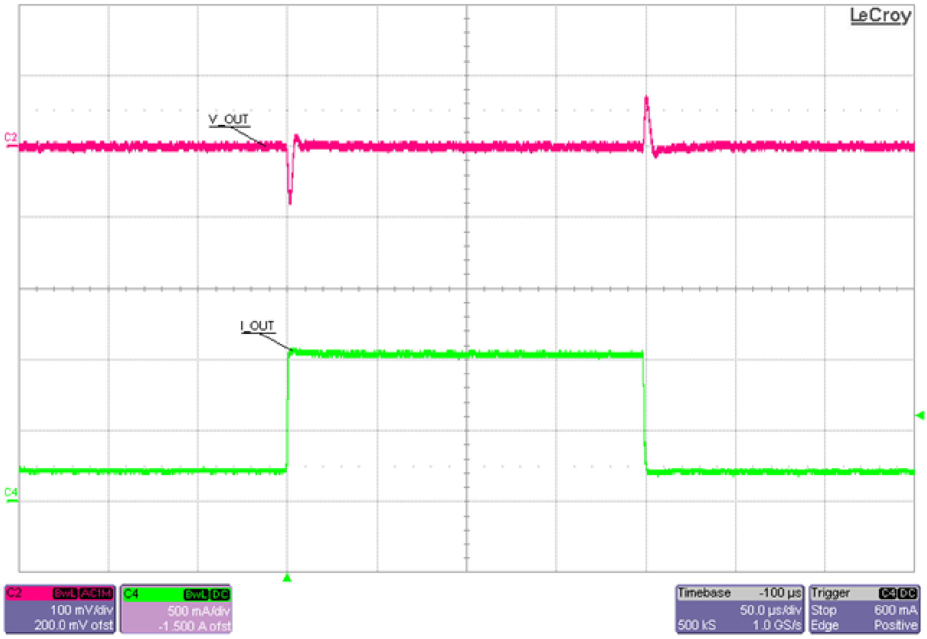


Figure 27. TPS62065-Q1 25-100%, 250 mA - 1 A Load Transient

3.2.4 Voltage Supervisor and Watchdog

Figure 28 to Figure 35 shows the voltage supervision of the system-voltage, core-voltage, and can-voltage power supplies. The supervisors are tested in overvoltage and undervoltage conditions. Propagation delay and reset time delay are also measured. Channel 1 (blue) measures the voltage supply and channel 2 (red) measures the $\overline{\text{RESET}}$ pin of the supervisor monitoring the respective voltage supply.

Figure 28 and Figure 29 shows the TPS3890-Q1 supervisor monitoring the CAN voltage rail. This device variant monitors a typical 5V rail with a 7% undervoltage tolerance. This means when the typical voltage fall below 4.65 V, the $\overline{\text{RESET}}$ pin will trigger an active-low voltage. When the sensed voltage comes back within the tolerance plus some hysteresis voltage, there is a reset delay which is programmed by an external capacitor to ground.

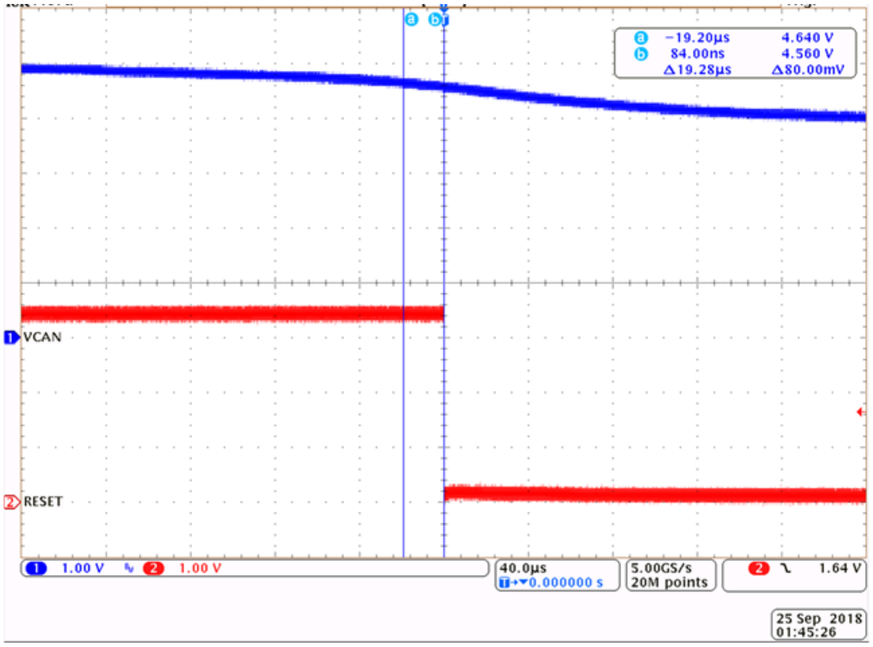


Figure 28. TPS3890-Q1 Undervoltage and Propagation Delay

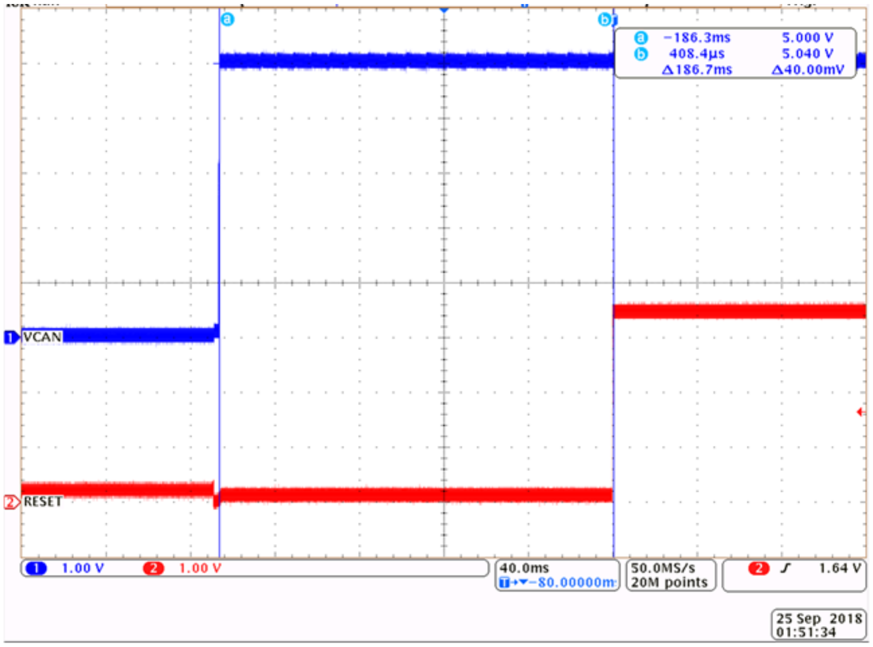


Figure 29. TPS3890-Q1 Start-Up and Reset Delay

Figure 30 through Figure 32 shows the TPS3703-Q1 window supervisor monitoring the core voltage rail. This device variant monitors a typical 1.2V rail with a 4% undervoltage and overvoltage tolerance. This means when the typical voltage fall below 1.152 V and above 1.248 V , the $\overline{\text{RESET}}$ pin will trigger an active-low voltage. When the sensed voltage comes back within the tolerance plus some hysteresis voltage, there is a reset delay which is programmed by pulling the CT pin up to VDD. The TPS3703-Q1 has also another fixed time delay option by leaving the CT pin open, or can be adjusted with an external capacitor.

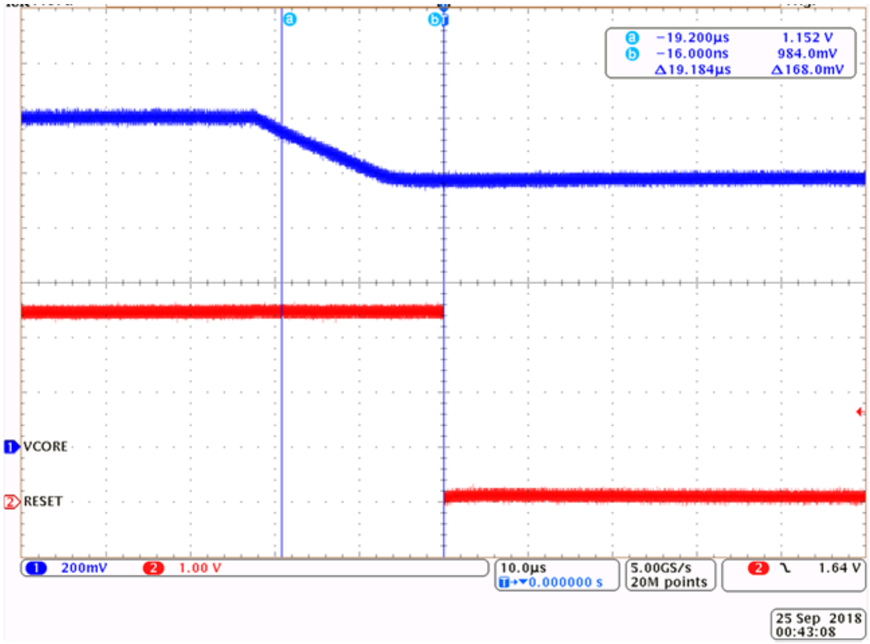


Figure 30. TPS3703-Q1 Undervoltage and Propagation Delay

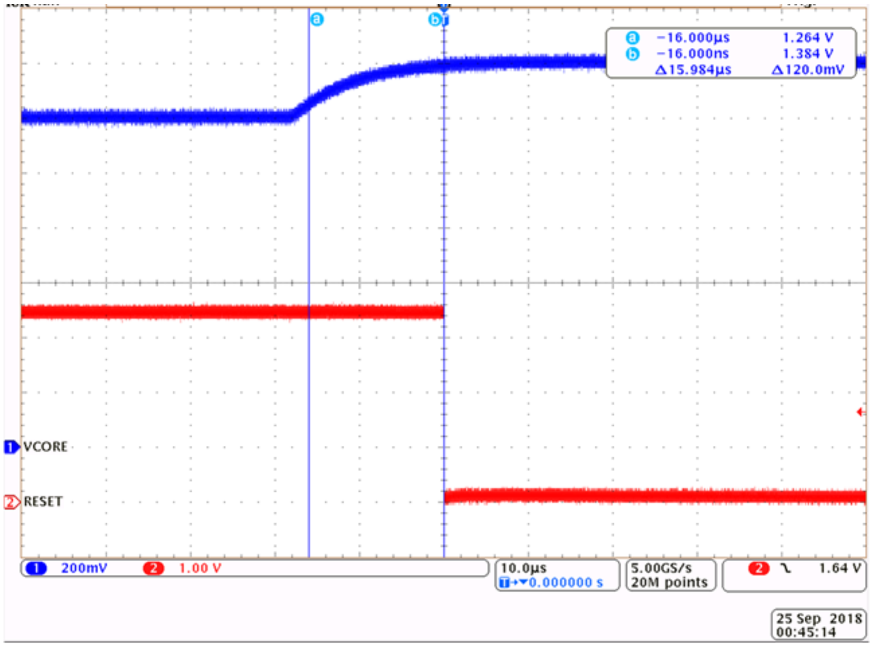


Figure 31. TPS3703-Q1 Overvoltage and Propagation Delay

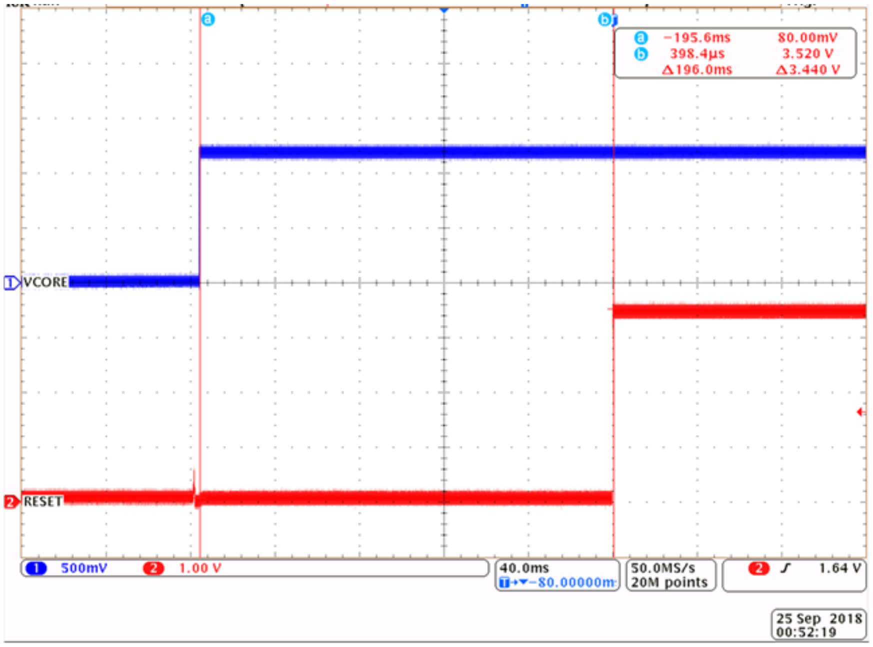


Figure 32. TPS3703-Q1 Start-Up and Reset Delay

Figure 33 through Figure 35 shows the TPS3850-Q1 window supervisor monitoring the system-power and I/O voltage rail. This device variant monitors a typical 3.3V rail with a 7% undervoltage and overvoltage tolerance. This means when the typical voltage fall below 3.069 V and above 3.531 V , the $\overline{\text{RESET}}$ pin will trigger an active-low voltage. When the sensed voltage comes back within the tolerance plus some hysteresis voltage, there is a reset delay which is programmed by leaving the CT pin open. The TPS3850-Q1 has also another fixed time delay by connected the pin to VDD, or can be adjusted with an external capacitor..

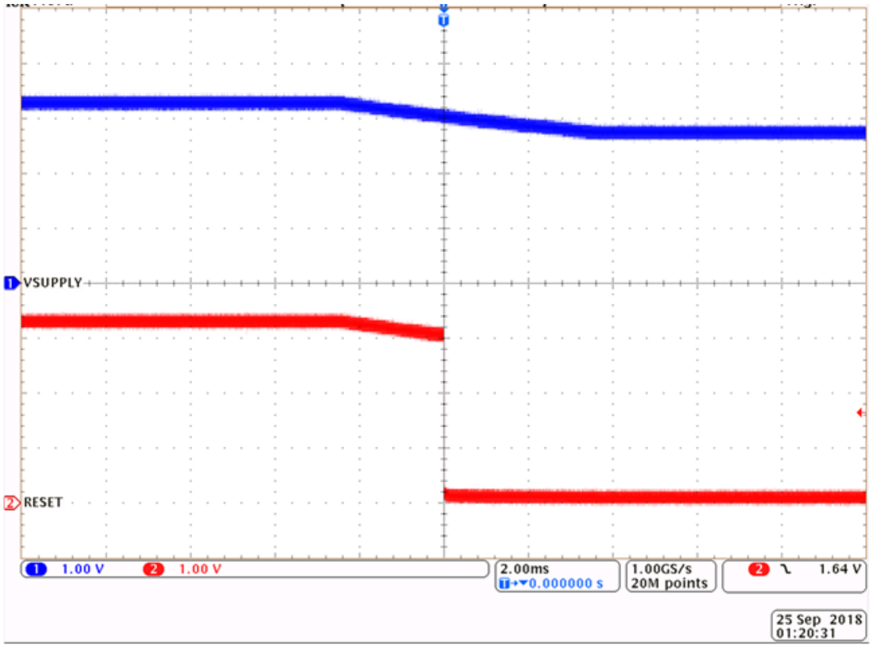


Figure 33. TPS3850-Q1 Undervoltage and Propagation Delay

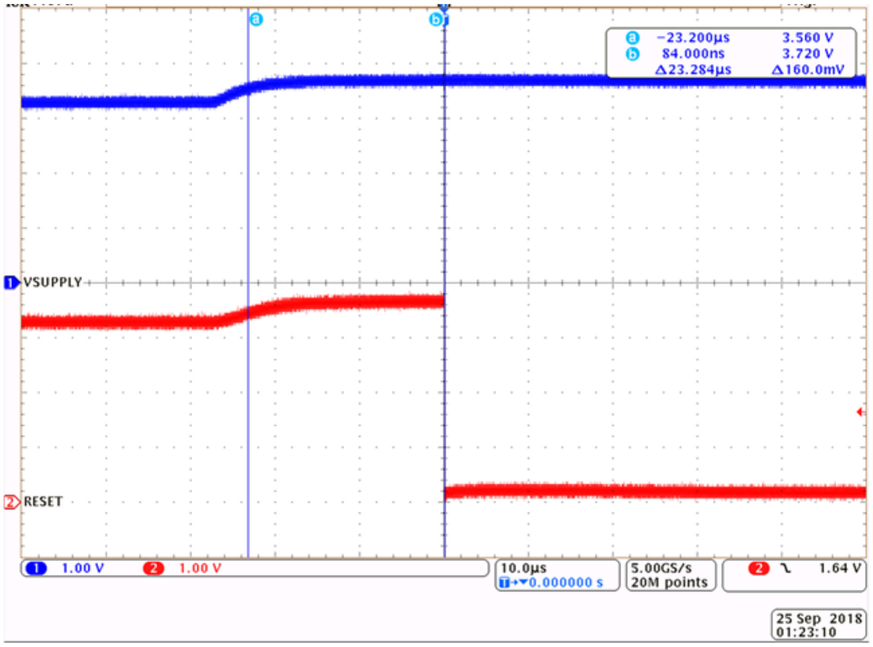


Figure 34. TPS3850-Q1 Overvoltage and Propagation Delay

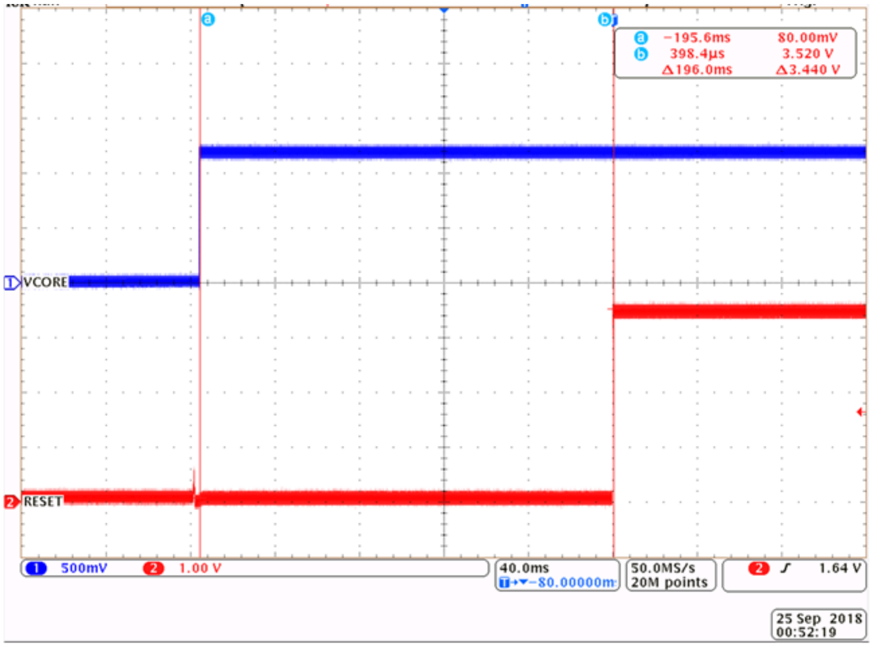


Figure 35. TPS3850-Q1 Start-Up and Reset Delay

The TPS3850-Q1 has an integrated window watchdog timer with adjustable window ratios and multiple fixed watching timing options. In this reference design, the TPS3850-Q1 utilizes a fixed watching timing option with a ½ window watchdog ratio. This means if the upper boundary of the watchdog timer is 1600 ms, then the lower boundary will 800 ms.

Figure 36 through Figure 39 shows the TPS3850-Q1 watchdog timer monitoring a WDI input waveform input at different frequencies. Figure 36 show a situation where the watchdog input waveform is absent. The watchdog timer output, WDO, stays a logic-high voltage until the upper boundary limit (1600 ms). Afterwards it is asserted to a logic-low voltage for a reset timeout period (200 ms). When it rises again to a logic-high voltage it will try to detect a falling edge on the watchdog timer input , WDI.

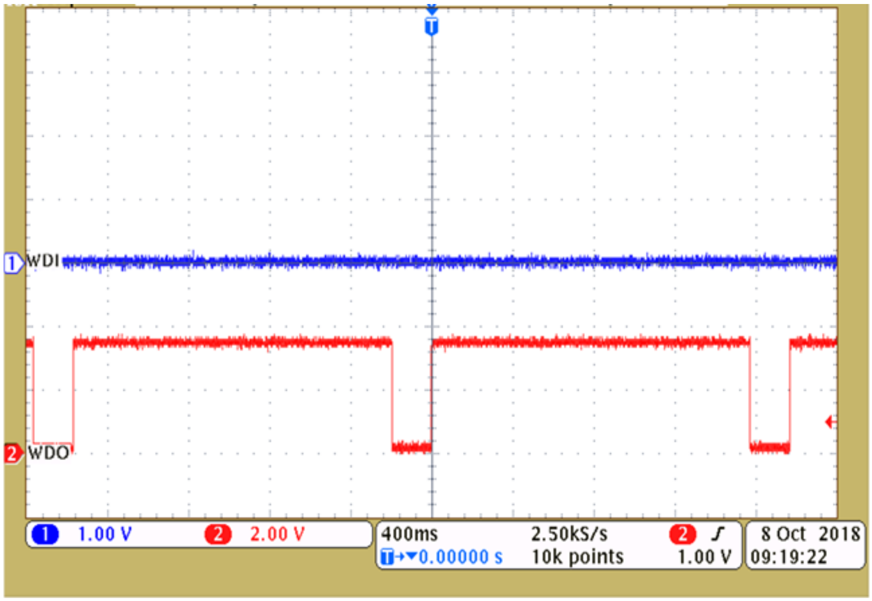


Figure 36. TPS3850-Q1 Watcher Timer 0 ms Period

Figure 37 shows the WDO signal when an acceptable input waveform is present on the WDI pin. The WDO pin stays high when the recurring falling edges fall between 800 ms and 1600 ms of the previous falling edge.

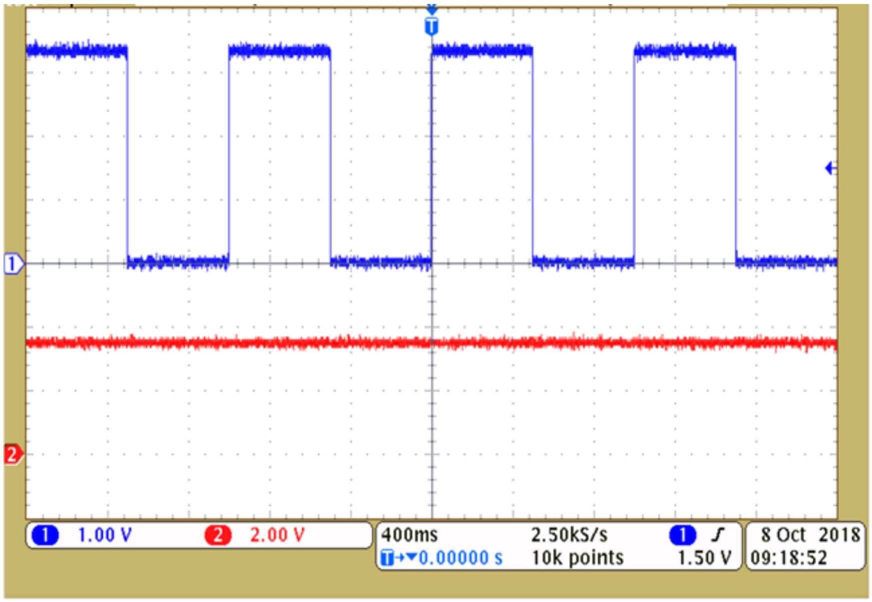


Figure 37. TPS3850-Q1 Watchdog Timer 1000 ms Period

Figure 38 shows an early detection fault found on the WDI input waveform. After the device reset timeout period (200 ms), it is asserted logic-high to detect the next falling edge. After detecting a falling edge, if another falling edge is found before the window lower boundary (800 ms), WDO will trigger to a logic-low voltage.

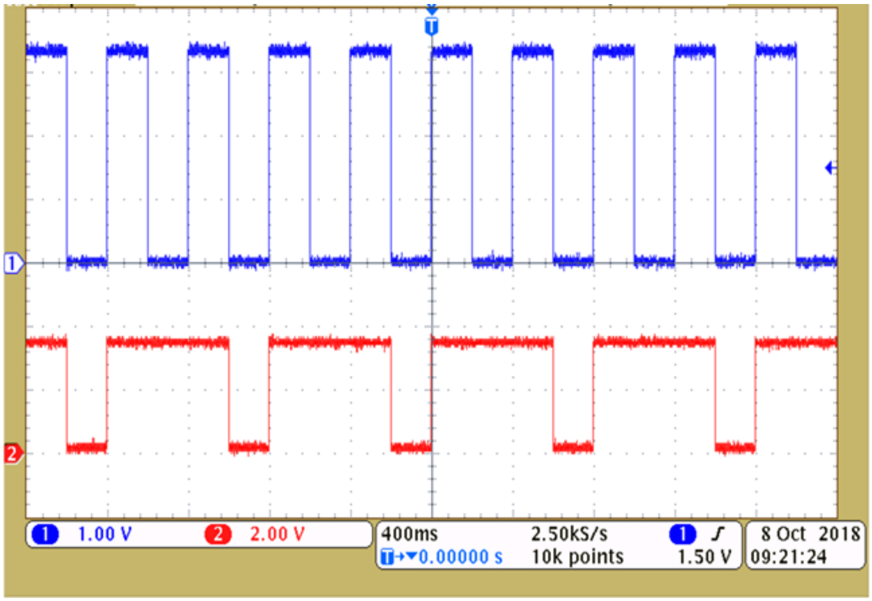


Figure 38. TPS3850-Q1 Watchdog Timer Early Detection 400 ms Period

Figure 39 shows an late detection fault found on the WDI input waveform. After the device reset timeout period (200 ms), it is asserted logic-high to detect the next falling edge. After detecting a falling edge, if another falling edge is not found within the window upper boundary (1600 ms), WDO will trigger to a logic-low voltage.

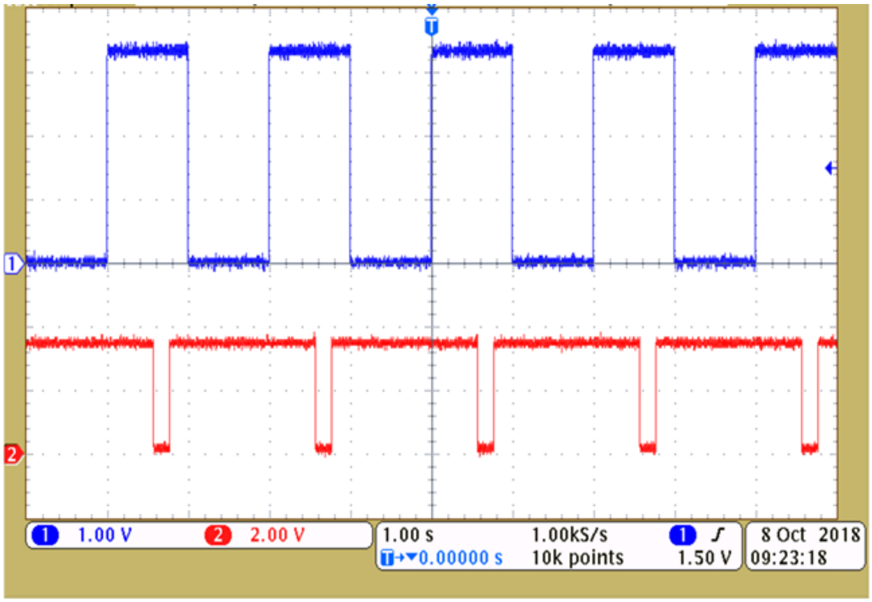


Figure 39. TPS3850-Q1 Watchdog Timer Late Detection 2000 ms Period

3.2.5 Voltage Reference Temperature Drift

Figure X shows the temperature drift of the LM4132-Q1 series voltage reference. See the LM4132-Q1 datasheet for more information and bench characteristics. Depending on the ADC specifications and accuracy requirements, the LM4128-Q1 or REF34-Q1 may be a better fit.

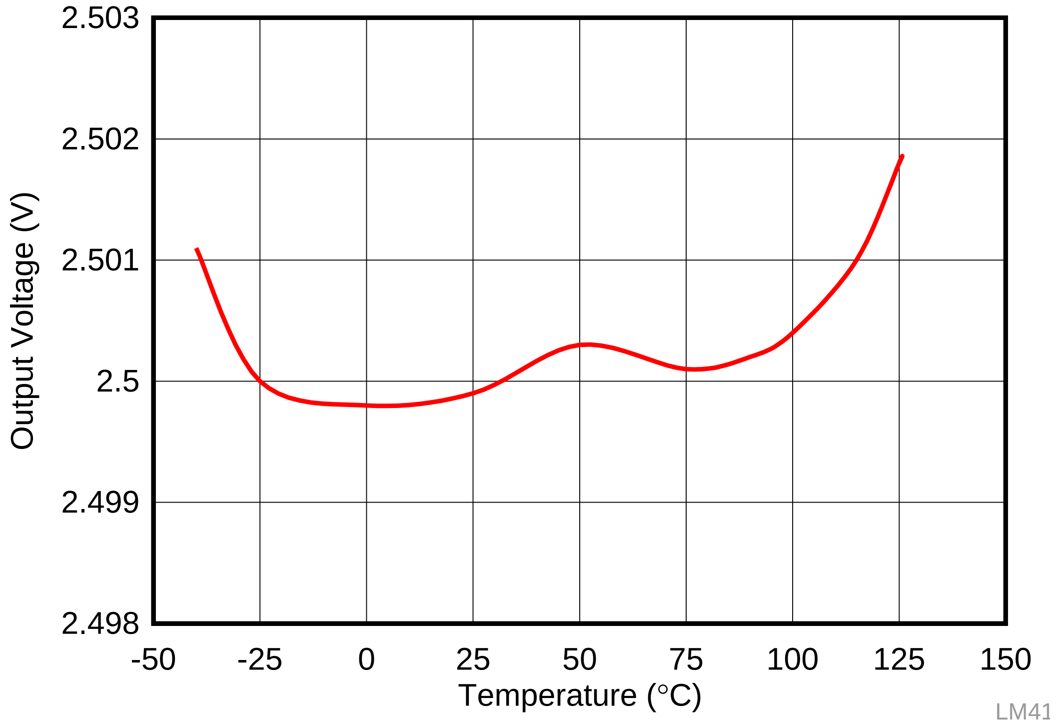


Figure 40. LM4132-Q1 Reference Voltage Temperature Drift

3.2.6 Thermal Images

Figure 41 through Figure 44 shows the temperature rise of each supply on the board under full load conditions and with a 13.5-V input voltage after 10 minutes.

NOTE: Board temperatures can exceed 55°C during operation.

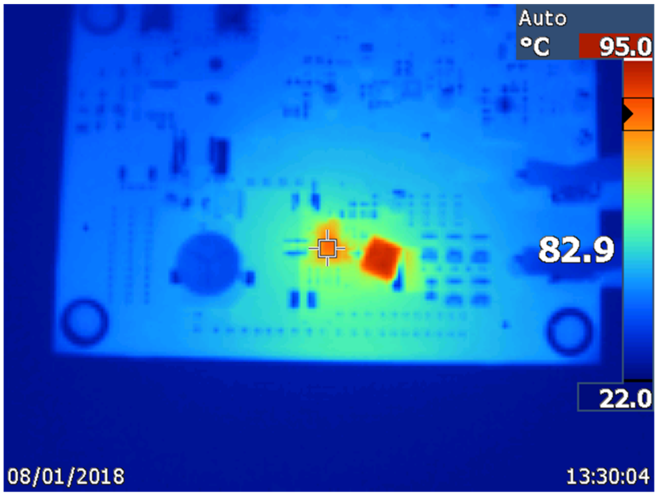


Figure 41. Thermal of LM73605-Q1 at 5-A Load

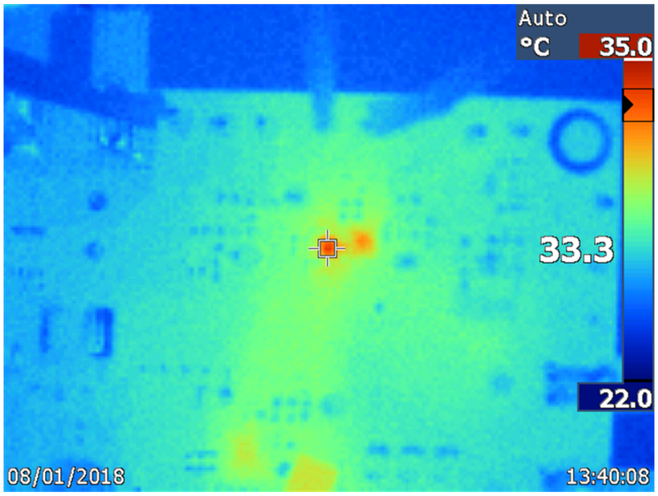


Figure 42. Thermal of TPS62065-Q1 at 1-A Load

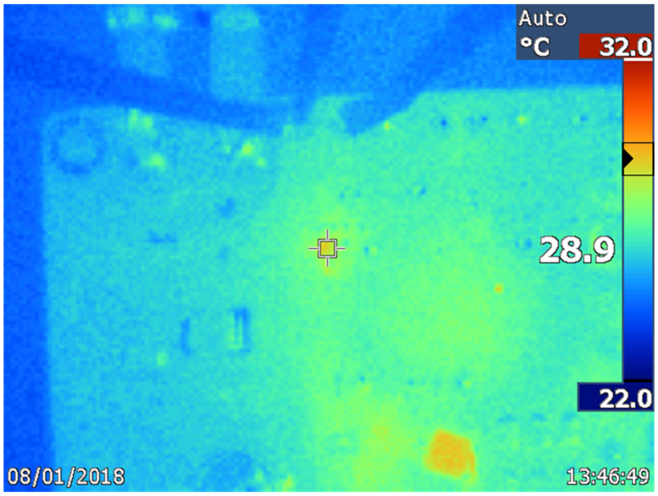


Figure 43. Thermal of TPS61240-Q1 at 200-mA Load

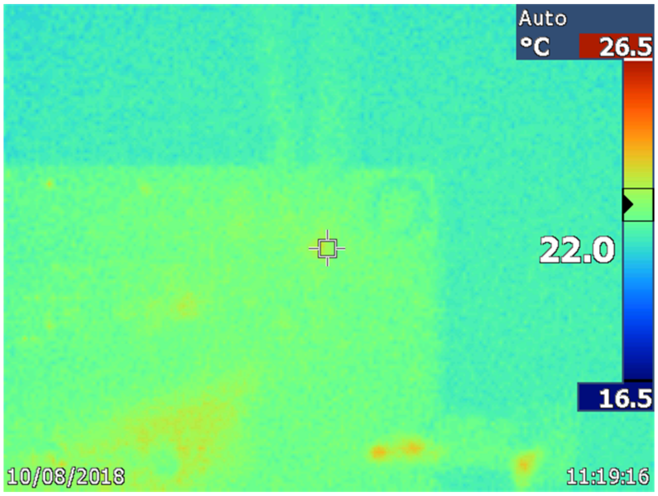


Figure 44. LM4132-Q1 at 20-mA Load

3.2.7 Electrical Transient Testing

The following transients were tested:

- Reverse battery
- Cold crank
- Warm crank
- Start-stop
- Start-up and shutdown

The following subsections show the waveforms of each rail during each condition.

3.2.7.1 Reverse Battery

The following Figure 45 shows that the input is disconnected during the reverse battery input voltage condition. Channel 1 (blue) is the input battery voltage that is connected to the source of the p-channel MOSFET and channel 2 (red) is connected of the drain of the P-FET and leads to the system EMI input filter and voltage input of the LM73605-Q1 wide vin buck converter.

The TLV1805-Q1 circuitry has been subjected to selected ISO 16750-2 and ISO 6737-2 waveforms for 12 V systems. The circuits survived with no performance degradation, and the load voltage did not exceed design limits. The circuit was tested on an evaluation module and does not imply full ISO certification of the board, or that the use of these circuits implies ISO certification of users end equipment. For more information, check the TLV1805-Q1 product page and datasheet.

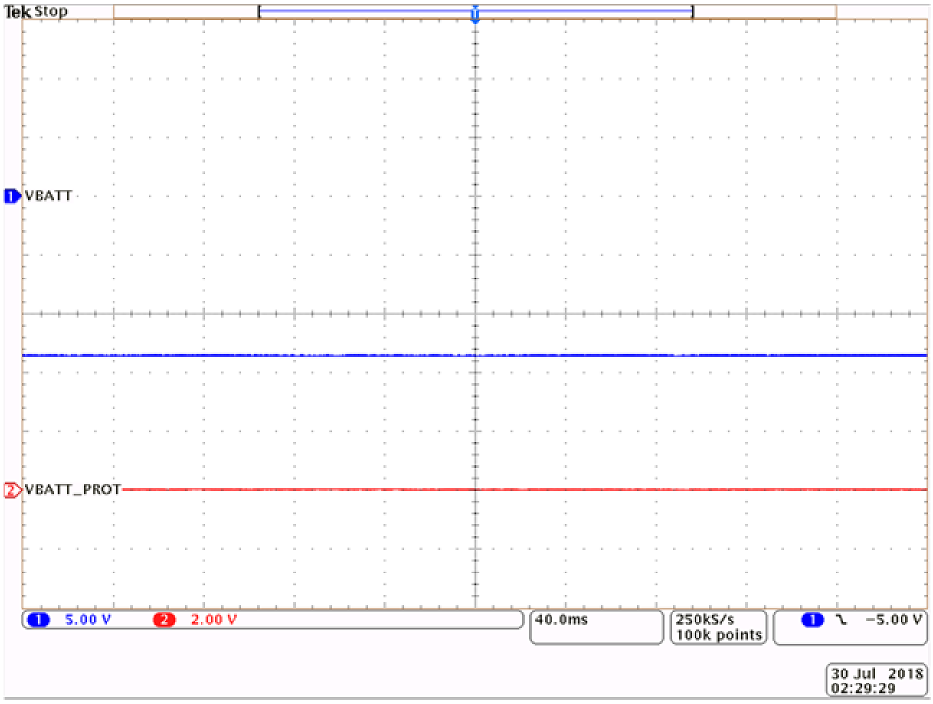


Figure 45. Continuous Reverse Voltage at Input

This behavior is expected from the TLV1805-Q1 comparator, where, upon a reverse voltage condition, the TLV1805-Q1 disconnects the MOSFET and prevents the reverse battery voltage from damaging the system components and board. Figure 46 shows the transition to reverse input voltage. The input voltage after the P-FET remains undisturbed as the voltage at the input becomes increasingly negative.

Figure 46. Transition to Reverse Voltage at Input

3.2.7.2 Cold Crank

Testing this design for a severe cold-crank condition was a key objective. This test was accomplished without using a pre-boost.

For the cold-crank test, the input voltage was allowed to fall to 3.5 V from the nominal 13.5 V. Figure 47 shows the cold-crank waveform.

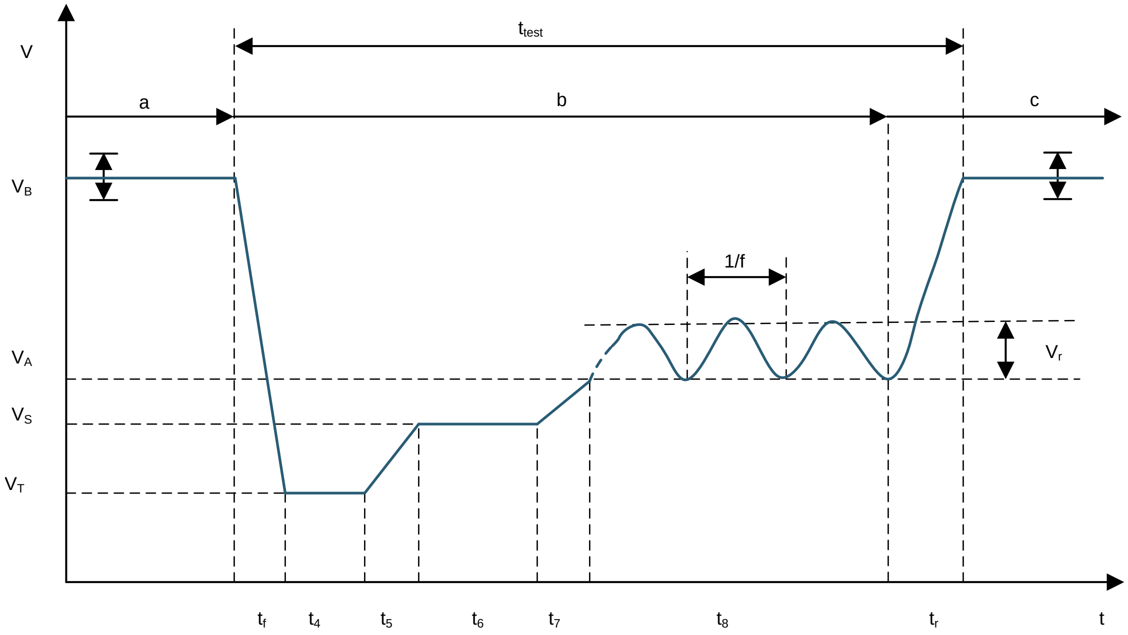


Figure 47. Cold-Crank Waveform and Parameters

Table 2 list the cold-crank test pulse parameters.

Table 2. Cold-Crank Test Pulse Parameters

PARAMETER	"NORMAL" TEST PULSE	"SEVERE" TEST PULSE
V_B	11.0 V	11.0 V
V_T	4.5 (0%, –4%)	3.2 V (0%, –4%)
V_S	4.5 (0%, –4%)	5.0 V (0%, –4%)
V_A	6.5 V (0%, –4%)	6.0 V (0%, –4%)
V_R	2 V	2 V
t_f	≤ 1 ms	≤ 1 ms
t_4	0 ms	19 ms
t_5	0 ms	≤ 1 ms
t_6	19 ms	329 ms
t_7	50 ms	50 ms
t_8	10 s	10 s
t_r	100 ms	100 ms
f	2 Hz	2 Hz

Only the severe test pulse was tested. The cold-crank condition lasts roughly 3s, after which it repeats. In Figure 48, channel 1 (blue) shows the cold-crank input voltage waveform, channel 2 (red) shows the 3.3-V system-supply voltage output.

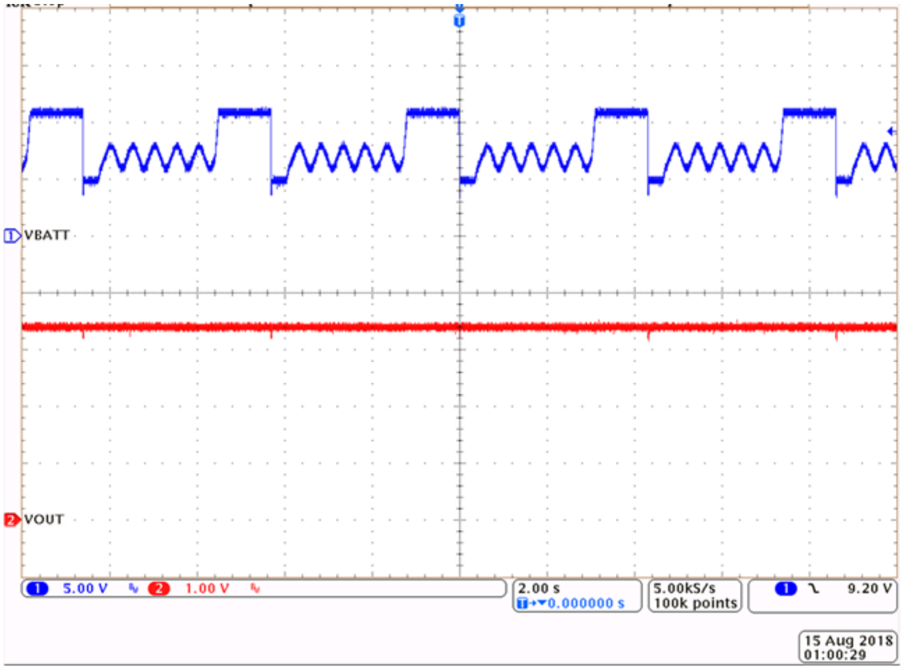


Figure 48. Cold Crank LM73605–Q1: 3.3 V at 5-A Output

Figure 49 shows the initial drop from 13.5 V to 3.5 V in a shorter timescale. The waveform shows the output voltage dips sightly, but is still within an operable voltage range. The dip is due to the forward voltage of the P-FET and EMI filter and dropout voltage of the LM73605-Q1.

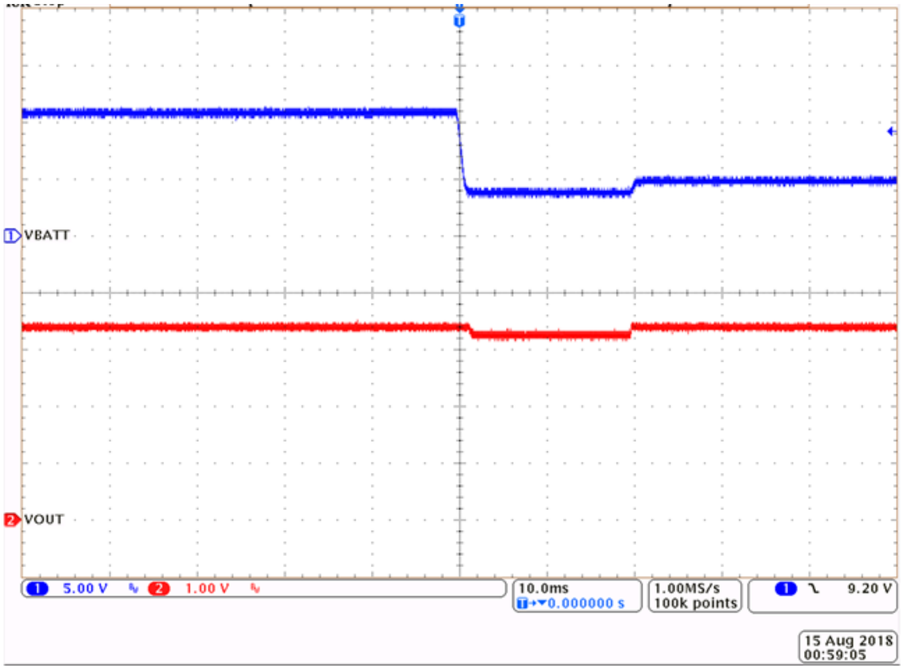


Figure 49. Cold Crank 10-ms Timescale, 3.3 V at 5-A Output

3.2.7.3 Warm Crank

This subsection provides test data for the main system supply during warm-crank conditions. In Figure 50 and Figure 51, channel 1 (blue) measures the warm-crank input voltage waveform, channel 2 (red) measures the 3.3-V main system supply.

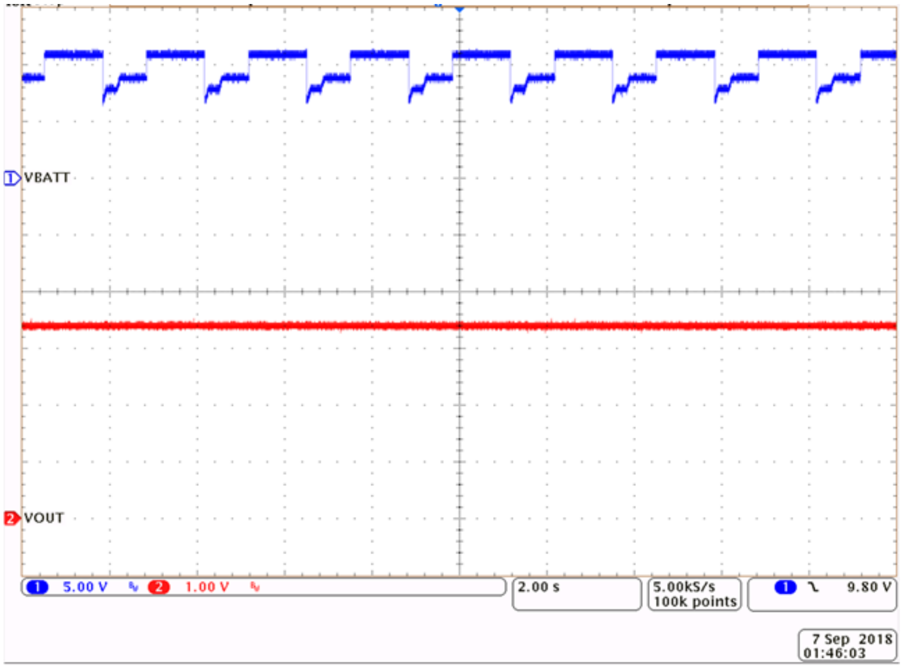


Figure 50. Warm Crank LM73605–Q1: 3.3 V at 5-A Output

Figure 51. Warm Crank 40-ms Timescale, 3.3 V at 5-A Output

3.2.7.4 Start-Stop

This subsection provides test data for the main system supply rail during start-stop conditions. In Figure 52 and Figure 53, channel 1 (blue) measures the start-stop input voltage waveform, channel 2 (red) measures the 3.3-V main system supply.

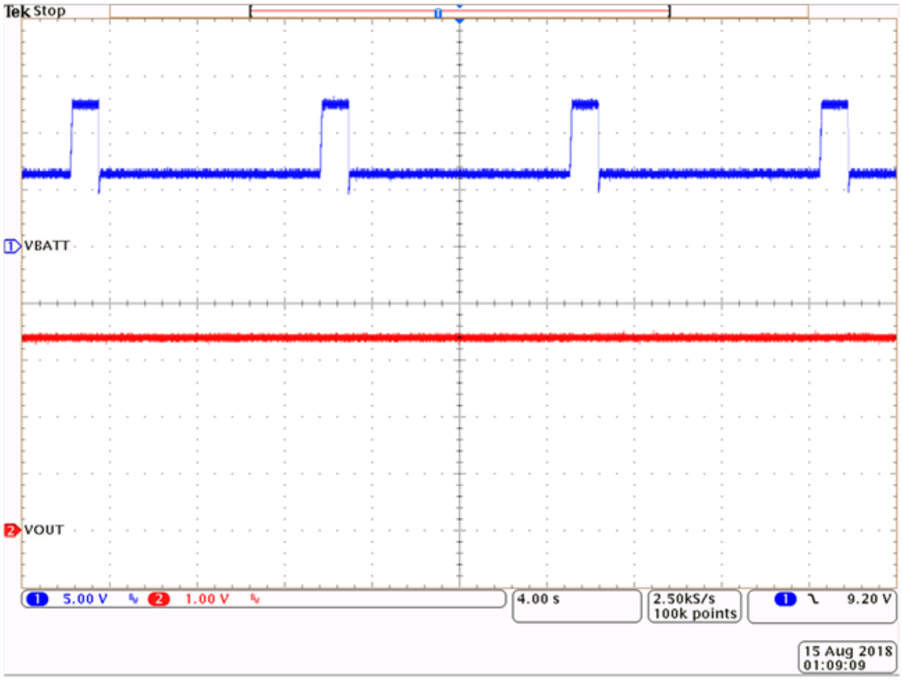


Figure 52. Start-Stop LM73605–Q1: 3.3 V at 5-A Output

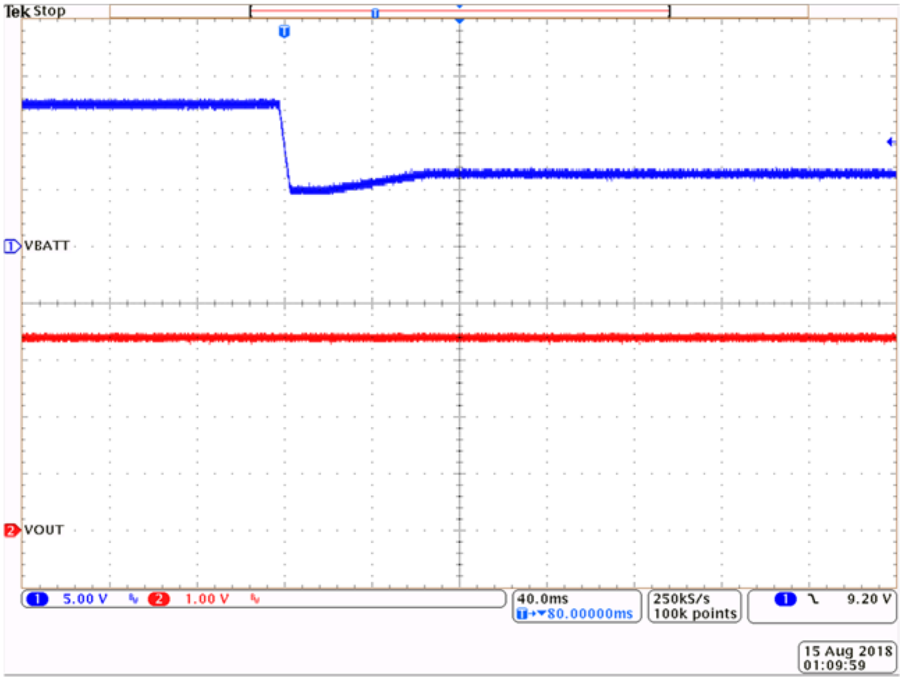


Figure 53. Start-Stop 40-ms Timescale, 3.3 V at 5-A Output

3.2.7.5 Start-Up and Shutdown

This subsection provides test data for the system-voltage (I/O), core-voltage, and CAN during system start-up and shutdown. Measurements were taken at full and no loads of the LM73605-Q1. Waveforms in Figure 54 and Figure 55 shows start-up behaviors. Waveforms in Figure 56 and Figure 57 shows shutdown behaviors.

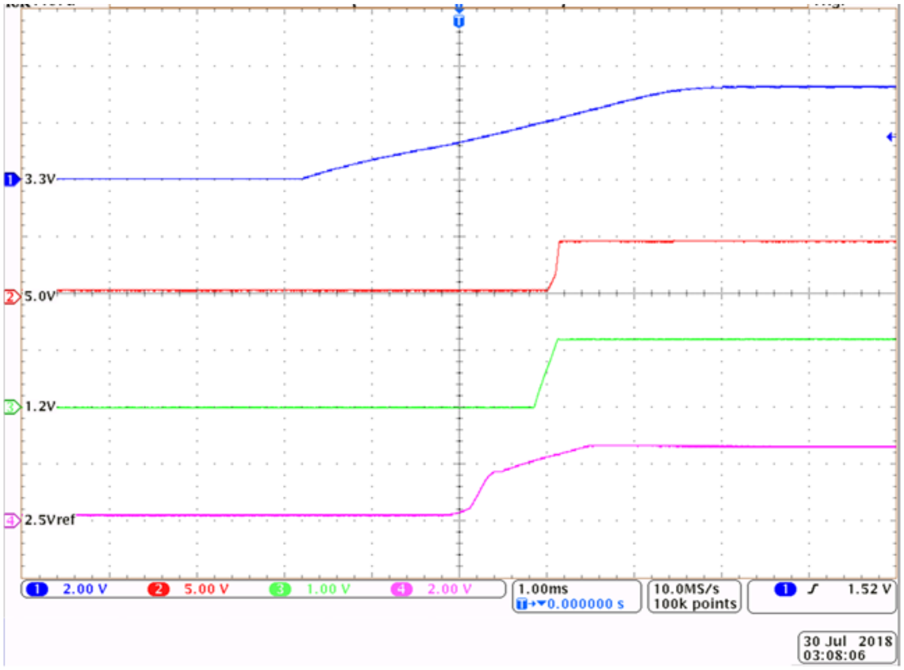


Figure 54. No Load Start-Up

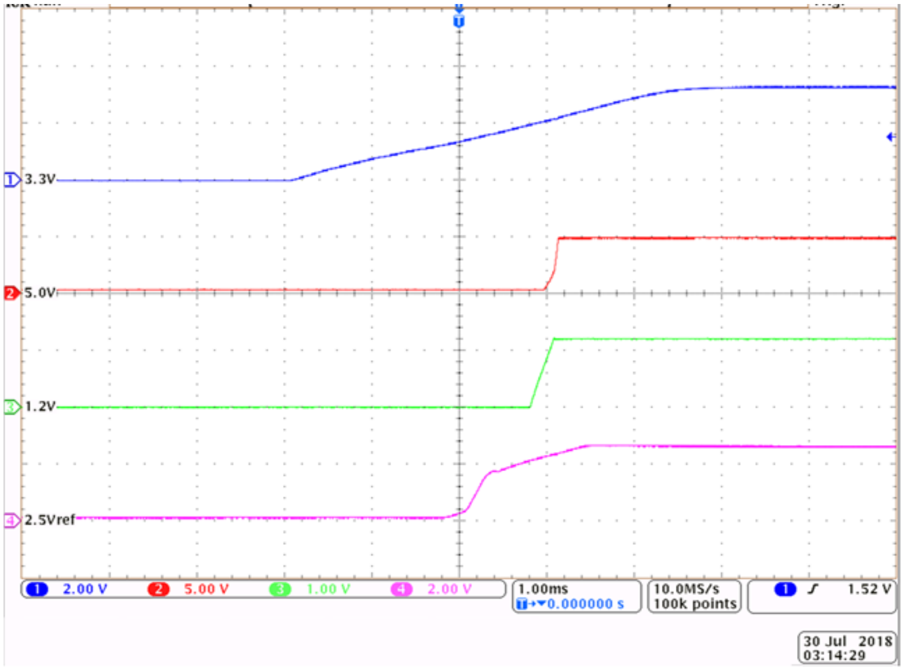


Figure 55. Full Load Start-Up

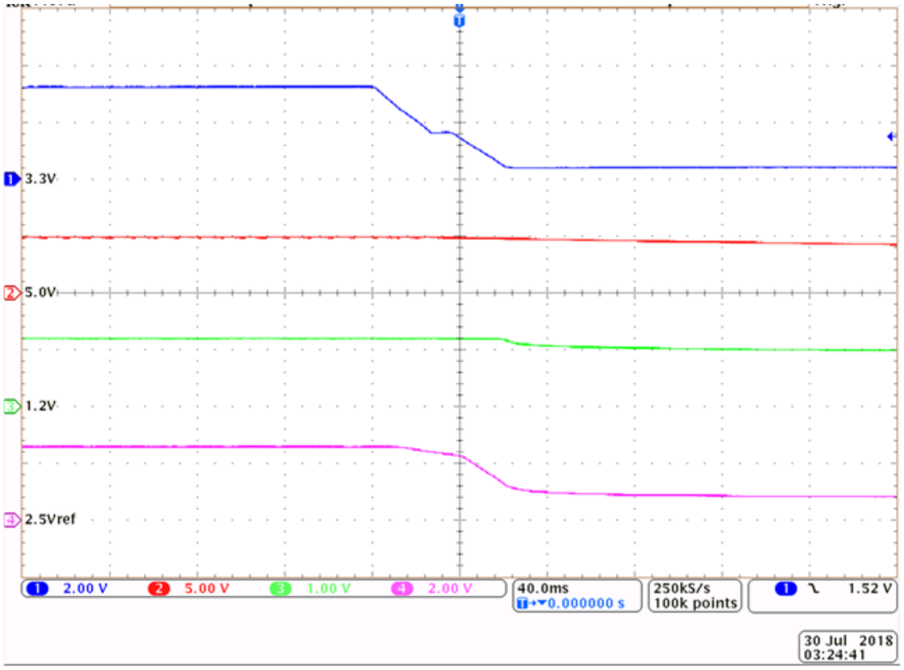


Figure 56. No Load Shutdown

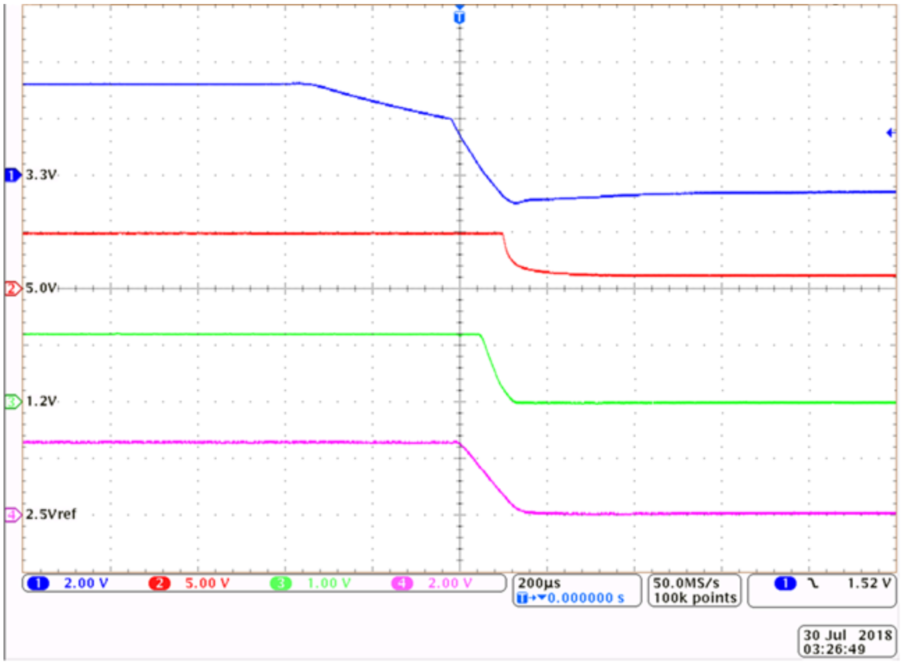


Figure 57. Full Load Shutdown

3.2.8 Conducted Emissions

The conducted emissions of the TIDA-050008 have been tested according to CISPR 25 Class 5 limit lines. The examined frequency band spans from 150 kHz to 108 MHz covering the AM-FM radio bands, very-high-frequency (VHF) band, and TV band specified in CISPR 25.

Figure 58 and Figure 59 show the test results. The limit lines (shown in red) are the Class 5 limits for conducted disturbances specified in the CISPR 25. The yellow trace (peak detector measurement) and blue trace (average detector measurement) are the measured results.

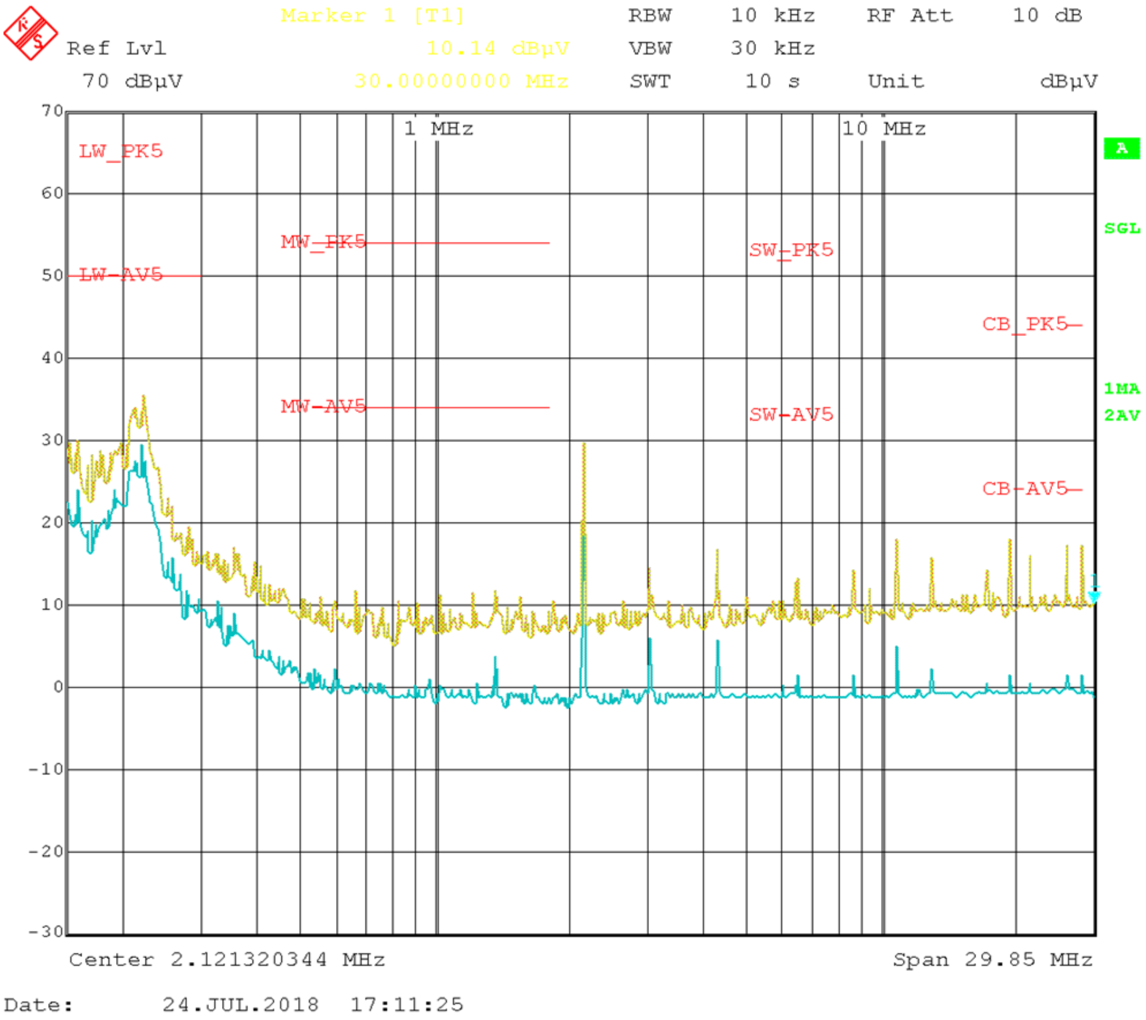


Figure 58. 150-kHz to 30-MHz Conducted Emissions—Peak and Average Detection

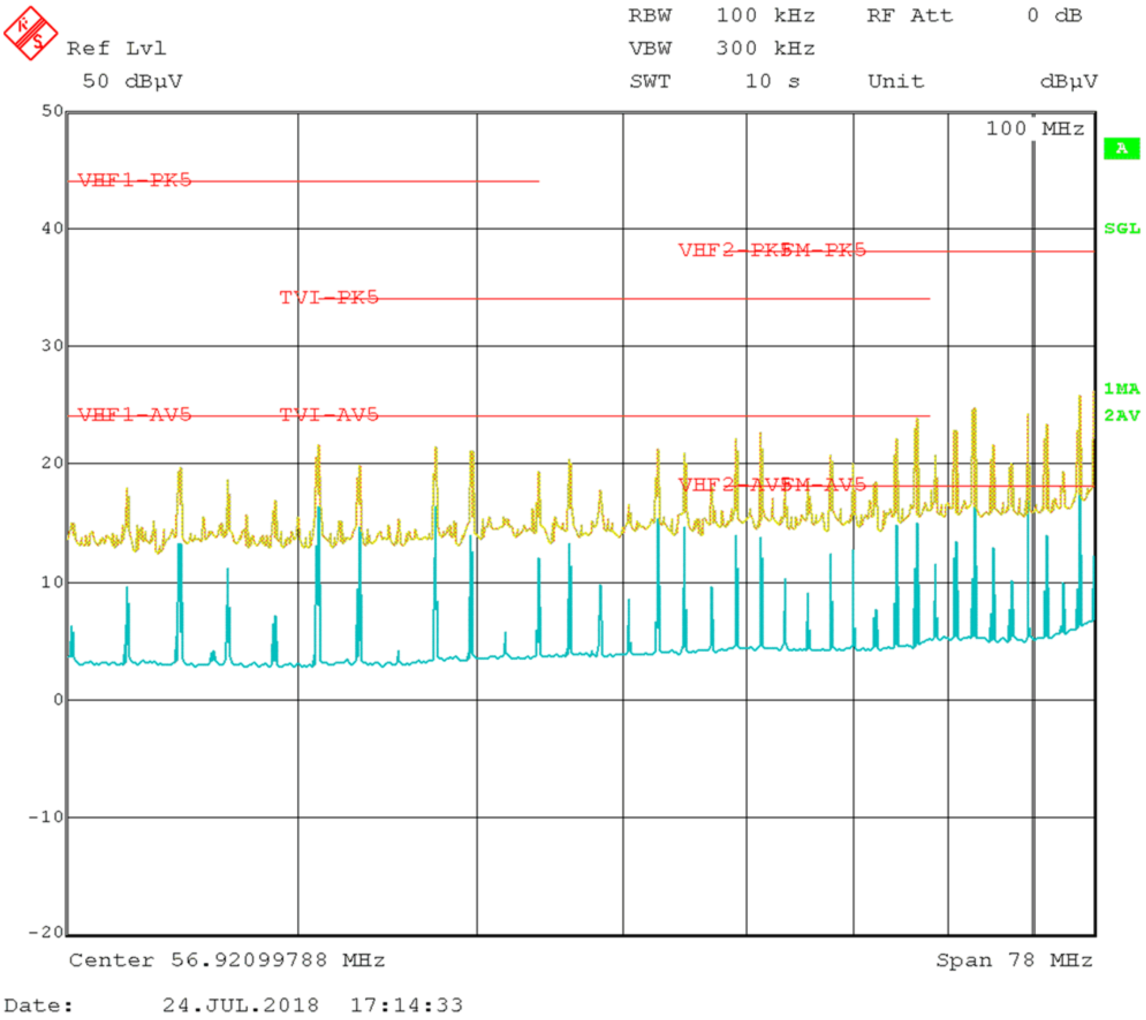


Figure 59. 30-MHz to 108-MHz Conducted Emissions—Peak and Average Detection

The conducted emissions were tested using the setup shown in Figure 60. The test setup uses 3, 2-Ω load resistors in parallel and covered with copper tape. The load resistors are directly connected to the output terminal copper pads of the LM73605-Q1 device.

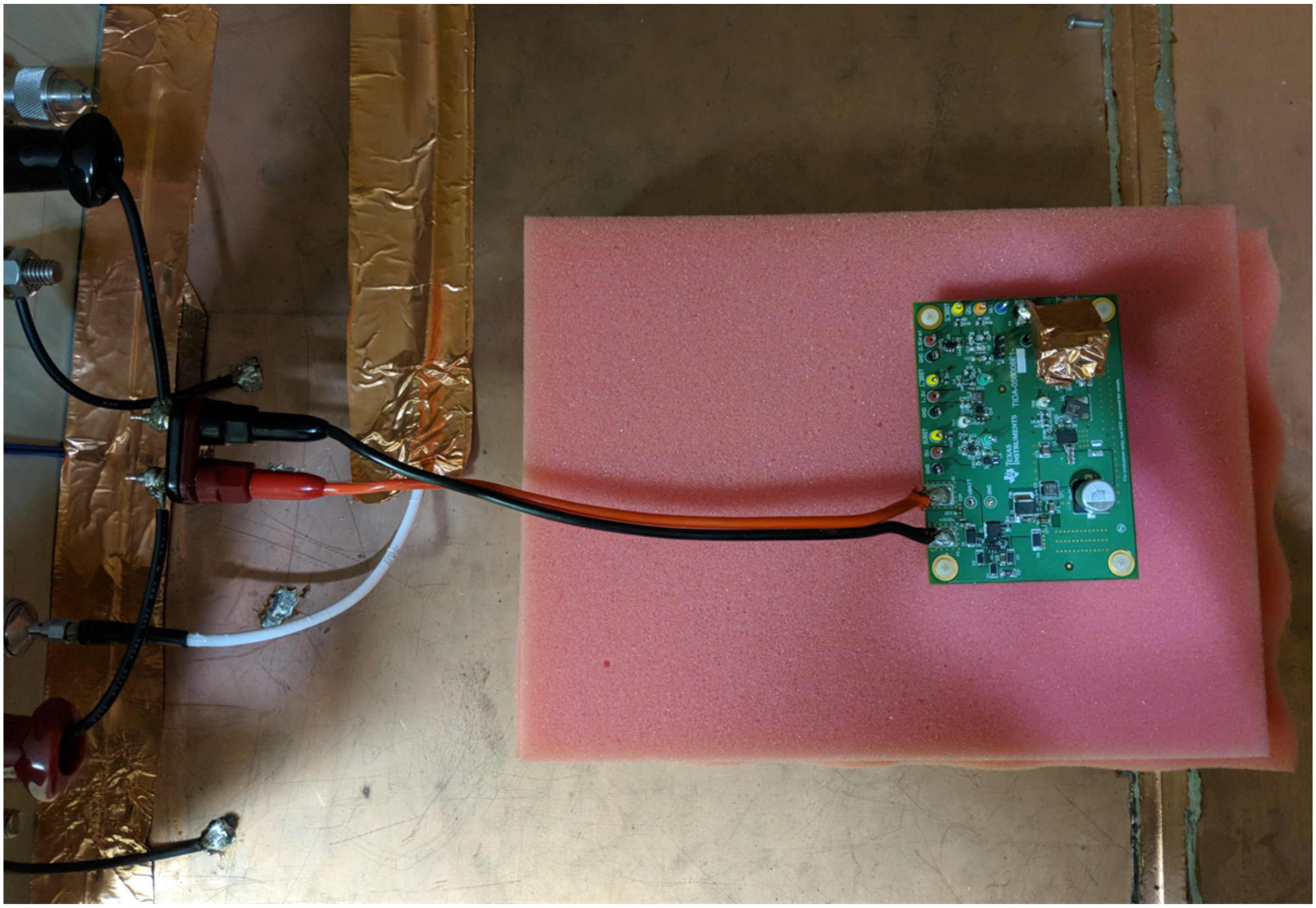


Figure 60. Setup for EMI Testing

4 Design Files

4.1 Schematics

To download the schematics for the board, see the design files at TIDA-050008.

4.2 Bill of Materials

To download the bill of materials for the board, see the design files at TIDA-050008.

4.3 Altium Project

To download the Altium Designer® project for the board, see the design files at TIDA-050008.

4.4 Gerber Files

To download the Gerber Files for the board, see the design files at TIDA-050008.

4.5 Assembly Drawings

To download the assembly drawings for the board, see the design files at TIDA-050008.

4.6 PCB Layout Recommendations

4.6.1 Input Protection Circuitry

Place input protection circuitry as close to the battery terminal inputs as possible, rather than close to the downstream circuit it is protecting, to reduce the inductance of the path. This placement allows the TVS diodes to react as quick as possible to any transients. Close placement provides a tight loop for the return path back to the battery terminals while the TVS diodes shunt a transient event. In the event of a reverse polarity event, the FET Q1 quickly shuts off, possibly causing inductive kicks due to the interrupted current flow. The severity of this kick is a function of the inductance and, therefore, the length and width of the power path.

4.6.2 Input EMI Filter Considerations

The goal of the EMI filter is to minimize emissions, especially conducted emissions. The key to minimizing emissions is providing low impedance paths to quickly ground high-frequency noise, which is typically accomplished by containing high-frequency current loops. Figure 61 shows the current flow through the EMI filter. The DC is outlined in red and the high-frequency AC paths are outlined in blue.

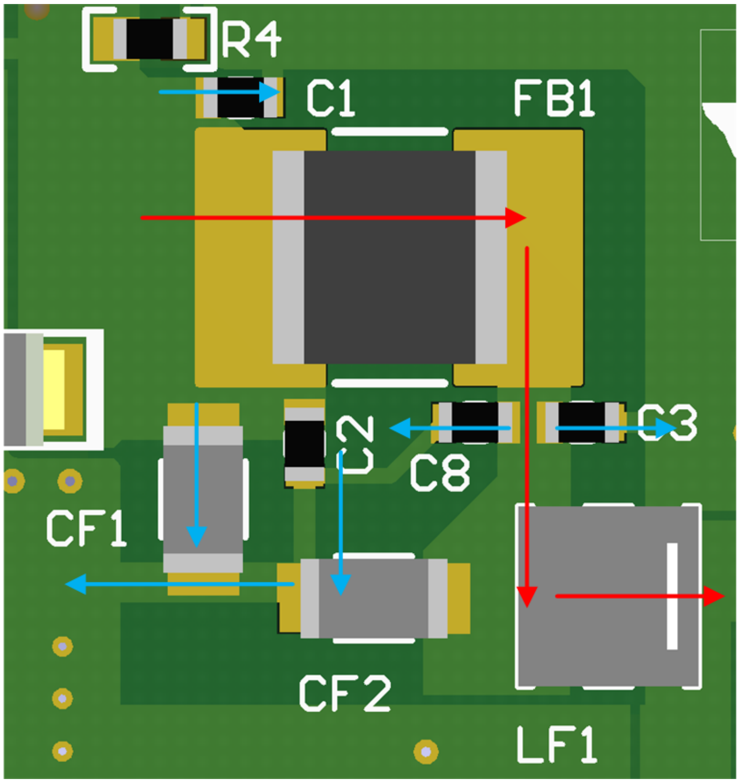


Figure 61. Input EMI Filter

Conducted emissions are mainly due to high-frequency noise that input capacitors cannot bypass. This noise is conducted onto the input leads of the supply, which drives the convention that the higher-frequency AC flows away from the 3.3-V supply back toward the system supply.

The previous Figure 61 shows the smaller 0.1-µF capacitors C3 and C8 close to the 2.2-µH inductor LF1 to filter out the high-frequency noise not attenuated by the inductor. Capacitors C3 and C8 are placed across from each other instead of next to each other to minimize the possibility of inductive coupling during operation due to their close proximity.

Inductors behave capacitively above their resonant frequency; therefore, any frequencies above this are not attenuated. The amount of noise that is injected back onto the supply line directly depends on how much has been filtered out; therefore, the smallest path to ground for high-frequency noise is required.

4.6.3 Noise-Sensitive Traces and Components

The feedback (FB) nodes of power supplies are especially high impedance and thus susceptible to picking up noise. These nodes are critical to operate the control loop of the device; therefore, poor placement and routing of these components or traces can affect the performance of the device and system by introducing unwanted parasitic inductances and capacitances.

The switch node of DC-DC converters are typically very noisy. The switch node can radiate a significant amount of energy and can couple noise into sensitive lines. Traces for the switch node must be wide enough for the maximum current but small enough to minimize radiation. Signals like output voltage FB traces for power supplies are high-impedance lines. These signals are quite sensitive to disturbances, especially to noise from switch nodes and high-bandwidth I^{2}C lines. The FB line must be routed away from noisy components and traces such as the switch node.

The TIDA-050008 layout in Figure 62 shows the current flow and FB for the main 3.3-V supply at the PCB level. The 3.3-V output voltage is sensed and fed back to the supply far enough from the switch node and high-frequency noise path to avoid noise coupling. Note resistor R20 is only populated for supervision test since connecting a floating test point to the FB pin is not ideal.

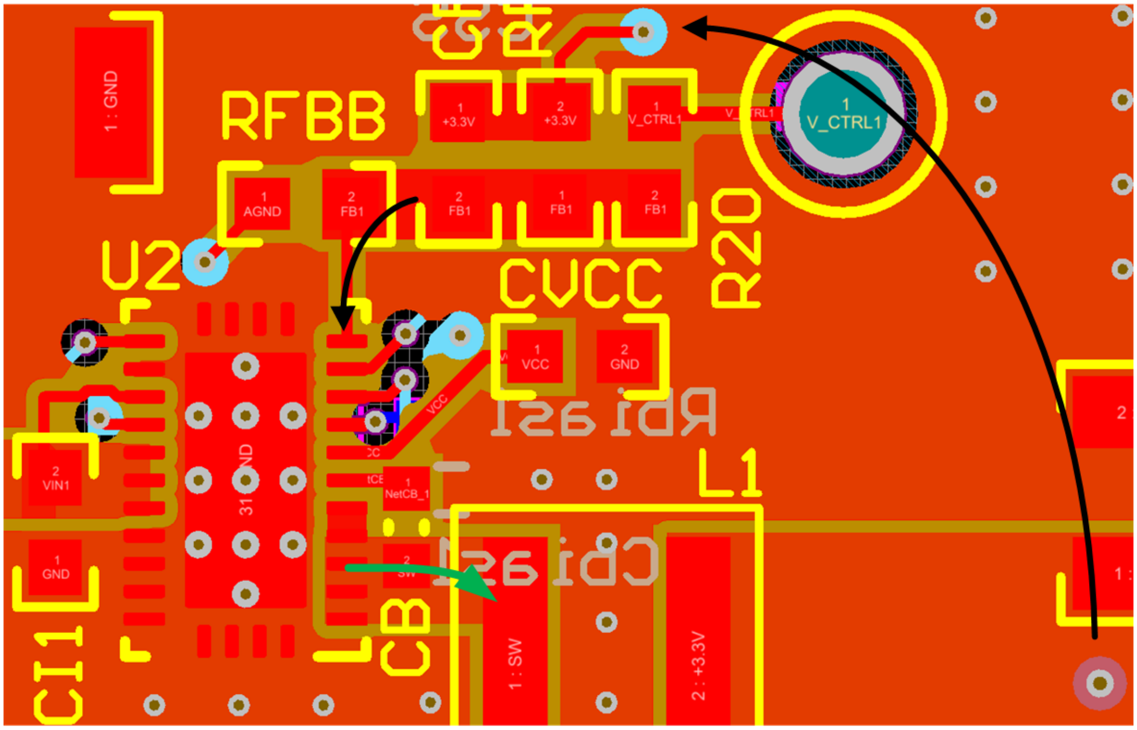


Figure 62. 3.3-V Supply Component and Node Placement

Create a separate analog ground for the feedback resistor network and net-tie it to the device thermal pad land of the PCB as a star point. Use common power PGND node and a different node for the signal AGND to minimize the effects of ground noise. In Figure 63, the red layer is the top layer and the light blue is the third layer, which contains the 3.3-V plane, analog ground plane, and several other signals and nodes. The black arrows show the current flow from the output through the feedback network to the dedicated analog ground plane connected to the GND thermal pad as the star point. The 3.3-V output voltage is sensed in the third layer of the board where the 3.3-V rail is quiet and distributed to the rest of the system.

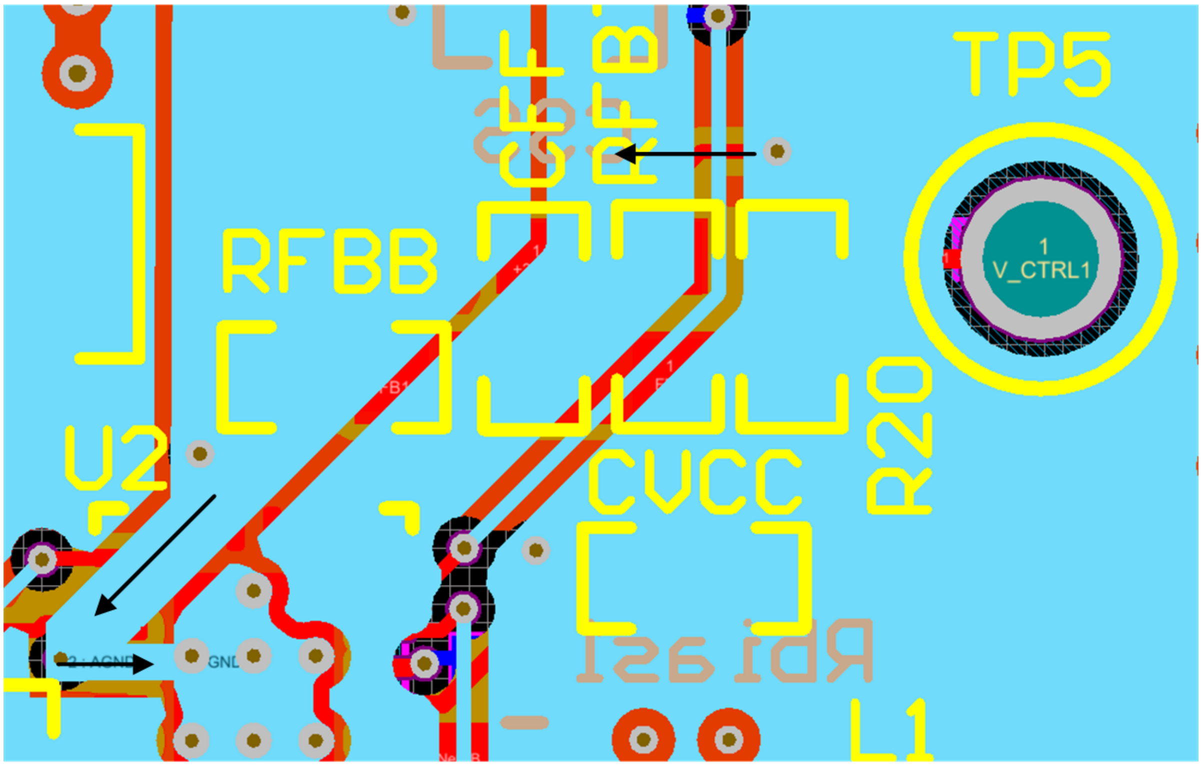
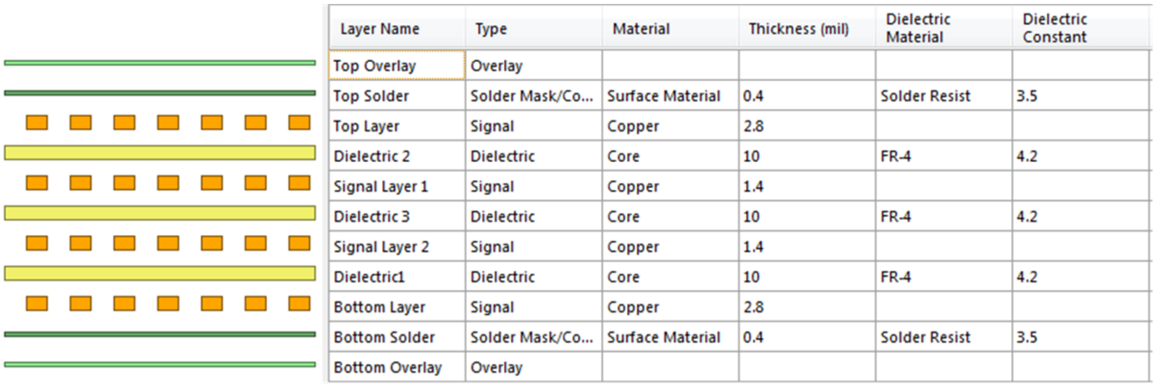


Figure 63. 3.3-V Output and Feedback Network

4.6.4 PCB Layering Recommendations

This reference design uses a four-layer board. Layer 2 is used as a dedicated ground plane. Layer 3 is used for the 3.3V power plane to provide power to the rest of the board. it is also used as a signal layer for certain routing circumstances. If using a six-layer board, make layers 2 and 5 ground planes to shield the internal signal layers from outside noise sources as well as the switch nodes found on the top layer. Figure 64 details the stack-up used in this reference design.



Layer Name	Type	Material	Thickness (mil)	Dielectric Material	Dielectric Constant
Top Overlay	Overlay				
Top Solder	Solder Mask/Co...	Surface Material	0.4	Solder Resist	3.5
Top Layer	Signal	Copper	2.8		
Dielectric 2	Dielectric	Core	10	FR-4	4.2
Signal Layer 1	Signal	Copper	1.4		
Dielectric 3	Dielectric	Core	10	FR-4	4.2
Signal Layer 2	Signal	Copper	1.4		
Dielectric1	Dielectric	Core	10	FR-4	4.2
Bottom Layer	Signal	Copper	2.8		
Bottom Solder	Solder Mask/Co...	Surface Material	0.4	Solder Resist	3.5
Bottom Overlay	Overlay				

Figure 64. Layer Stack-Up With GND Planes Separating Signal Layers

Keep power traces and pours on the same layer as much as routing requirements allow. This grouping minimizes the inductance of the path and reduces noise coupling between planes. Unfortunately, due to the high number of rails in this reference design and the routing requirements required to get signals to the EVM connectors, sticking to this rule is not totally possible.

5 Related Documentation

1. Texas Instruments, *LM73605/LM73606 3.5-V to 36-V, 5-A or 6-A Synchronous Step-Down Voltage Converter*
2. Texas Instruments, *TLV1805-Q1 Push-Pull High Voltage Comparator*
3. Texas Instruments, *TPS3703-Q1 High-Accuracy Window Supervisor*
4. Texas Instruments, *TPS3850-Q1 Precision Voltage Supervisor with Programmable Window Watchdog Timer*
5. Texas Instruments, *TPS3890-Q1 Low Quiescent Current Precision Supervisor*
6. Texas Instruments, *AN-2155 Layout Tips for EMI Reduction in DC/DC Converters*

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