TI Designs

±100-A ,<1% Accurate, Shunt-Based, High-Side, Bidirectional Current Measurement Reference Design

Description

This TI Design provides a reference solution for ±100-A shunt-based, high-side continuous bidirectional current measurement addressing applications such as battery current monitoring and current monitoring in UPS, telecom rectifiers, and server PSUs. This design achieves high accuracy with a low shunt resistance value, thus reducing power loss and hence shunt sizing.

Resources

TIDA-01141	Design Folder
INA240	Product Folder
LM4041	Product Folder
LM393	Product Folder

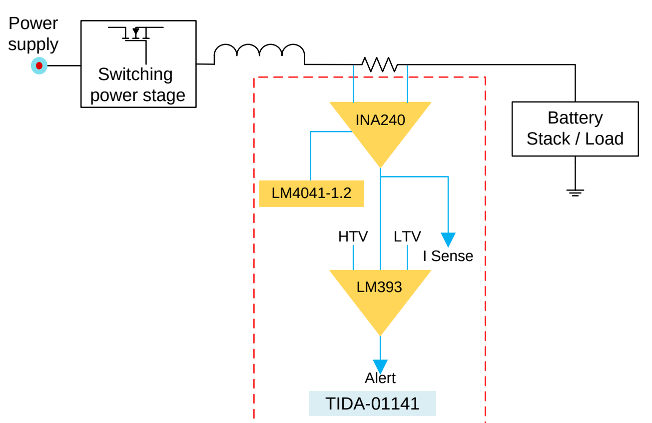
TI E2E™ Community — ASK Our E2E Experts

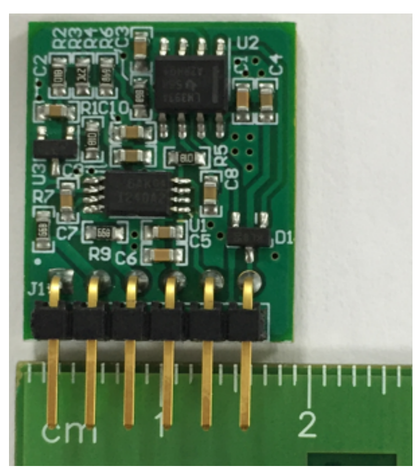
Features

- Shunt-Based ±100-A Continuous Bidirectional Current Measurement Solution for Accurate Current Monitoring Applications
- Tight DC Accuracy of <1% Across Temperatures From –25°C to 85°C
- Low Shunt Value Offers Reduced Power Loss and Enhances System Efficiency
- High-Side Current Sense Solution Batteries Ranging From 6 to 60 V (12 V/24 V/36 V/48 V) and Common-Mode Voltage up to 80 V
- Scalable Solution to Measure Low and High Currents, Which Can Interface Directly With Differential or Single-Ended ADC
- Fast (<10-µs) Overcurrent Fault Alert in Either Direction for System Safety With Programmable Threshold
- Adaptable for Current Sensing Even Close to Fast Switching Nodes Without Any External Common-Mode Filtering

Applications

- Battery Chargers
- UPS
- Energy Storage Systems
- Battery Management Systems
- DC Bus Protection





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

1 System Overview

1.1 System Description

Current measurement is vital in many electronic systems. Knowing the amount of current flowing is useful in a variety of applications in switch mode power supplies (SMPS) like DC bus protection, UPS, energy storage systems, and so on. These applications require current sensing for control and monitoring purposes.

Different current measurement methods exist that perform current sensing such as Hall effect devices, current transformers, shunt resistors, and so on. These magnetic based solutions offer isolation benefits but are not cost effective.

Shunt-based current sensing can be classified into high-side current sensing or low-side current sensing systems. In high-side current sensing systems, the current sense resistor is typically placed in series with the hot wire and positive supply line. In low-side current sensing systems, the sense resistor is usually placed in series with the GND terminal.

High-side current sensing poses many challenges when compared with low-side current sensing. One of the major challenges posed by high-side current sensing is the presence of high-side common-mode voltage.

Low-side current sensing seems easier to implement as it does not suffer from the high common-mode voltage issue, but it has certain disadvantages that prohibit its use for certain applications. One of the limitations is that because low-side sensing circuits take the GND as reference, any disturbance in the system GND can reflect in the output. Another disadvantage is that in case of a system fault leading to short circuit by passing the current sense resistor, the low-side current sensing circuit will fail to detect this short circuit condition. These disadvantages make high-side current sensing a good choice for applications like battery monitoring systems, load current monitoring in UPS, and energy storage systems. Figure 1 and Figure 2 show the usage scenario.

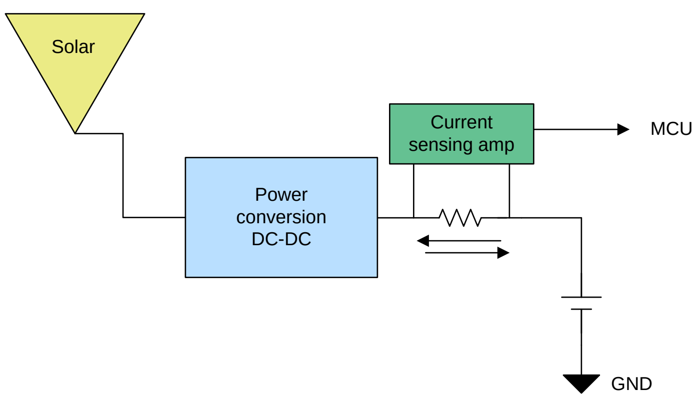


Figure 1. Energy Storage Systems

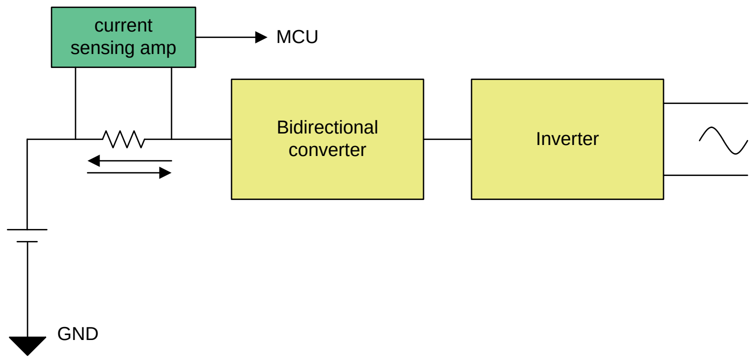


Figure 2. UPS

As highlighted in this section, high-side current sensing comes with many challenges. It is difficult to implement them using standard op-amp based differential amplifier circuits. Dedicated current sense amplifiers are very well suited for implementing high-side current sensing.

The major advantage current sensing amplifiers offer over op amps is that they are capable of operating with high common-mode voltage, extending above their supply voltage.

Current sense amplifiers also integrate the gain network (resistors) inside the package. When compared with a traditional differential amplifier circuit this offers a huge advantage because using external resistors in a circuit with high common-mode voltage, can lead to high gain errors and degradation in the overall CMRR of the system. By integrating the resistors in the current sense amplifiers package, the CMRR of the system is improved at the same time these resistors will be well matched for performance over varying temperature.

The TIDA-01141 reference design provides a low-cost solution based on the INA240 current sense amplifier that uses shunt based current sensing mechanism. The output of the INA240 is given as one of the outputs of this TI Design and can be directly interfaced with an MCU through the ADC peripheral. The INA240 output is also internally compared with a high and low threshold using a comparator for bidirectional overcurrent detection. The comparator is used to generate fast (< 10 µs) overcurrent fault interrupts for system safety.

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETER	TEST CONDITIONS	MIN	NOM	MAX	UNIT
INPUT CONDITIONS					
Input supply voltage (V_{CCI}	—	3.2	3.3	3.4	V
Input common-mode voltage range	—	–4.0	—	80.0	V
Input differential voltage range	—	–20.0	—	36.0	mV
SYSTEM SPECIFICATIONS					
Current amplifier gain	—	—	50.0	—	
Accuracy	At 25°C	—	0.2	1.00	%
	From –25°C to 85°C	—	0.2	1.00	%
Propagation delay	With 100-kHz triangular wave, 5 mVp-p	0.50	1.2	1.50	µs
Overcurrent fault set-point	Output level, forward direction	2.85	2.9	2.95	V
Overcurrent fault set-point	Output level, reverse direction	0.55	0.6	0.65	V
Operating ambient	—	–25.00	25.0	85.00	°C
Board size	Length × Breadth × Height	22 × 18.5 × 3			mm

1.3 Block Diagram

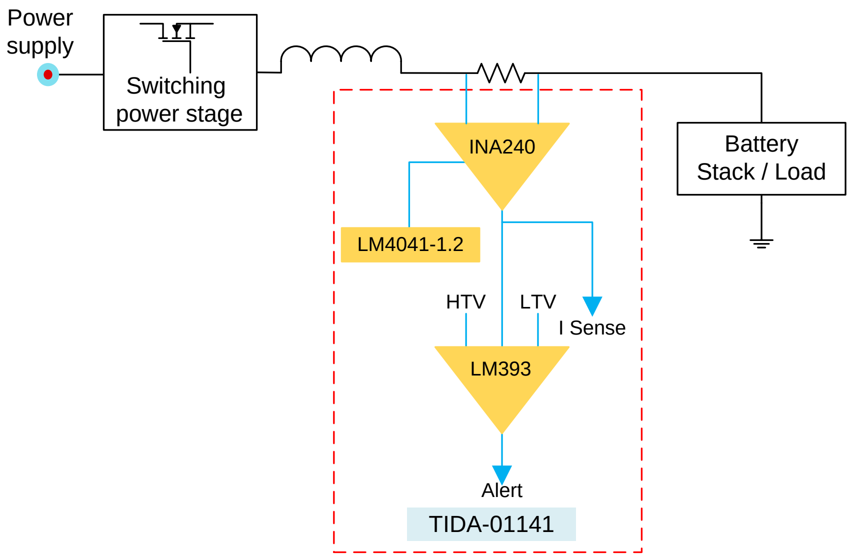


Figure 3. TIDA-01141 Block Diagram

Figure 3 shows the high-level block diagram of circuit. The main parts of this design are the current sense amplifier (INA240), shunt voltage reference (LM4041), and comparator (LM393).

1.4 Highlighted Products

This TIDA-01141 reference design features the following devices which were selected based on their specifications. The key features of the highlighted products are mentioned as follows. For more information on each of these devices, see their respective product folders at www.TI.com or click on the links for the product folders on the first page of this reference design.

1.4.1 INA240

The INA240 is a voltage-output, current-sense amplifier with enhanced PWM rejection that can sense drops across shunt resistors over a wide common-mode voltage range from –4 to 80 V, independent of the supply voltage. The negative common-mode voltage allows the device to operate below ground, accommodating the flyback period of typical solenoid applications. Enhanced PWM rejection provides high levels of suppression for large common-mode transients (dV/dt) in systems that use pulse width modulation (PWM) signals (such as motor drives and solenoid control systems). This feature allows for accurate current measurements without large transients and associated recovery ripple on the output voltage. The INA240 is available with fixed gain (20 V/V, 50 V/V, 100 V/V, and 200 V/V). See Table 2:

Table 2. Device Comparison Table for INA240

PRODUCT	GAIN (V/V)
INA240A1	20
INA240A2	50
INA240A3	100
INA240A4	200

1.4.2 LM4041

The LM4041-N is a precision voltage reference. The advanced design of the LM4041-N eliminates the need for an external stabilizing capacitor while ensuring stability with any capacitive load, thus making the LM4041-N easy to use. Further reducing design effort is the availability of a fixed (1.225 V) and adjustable reverse breakdown voltage. The minimum operating current is 60 µA for the LM4041-N 1.2 and the LM4041-N ADJ. Both versions have a maximum operating current of 12 mA. The LM4041-N uses fuse and Zener-zap reverse breakdown or reference voltage trim during wafer sort to ensure that the prime parts have an accuracy of better than ±0.1% (A grade) at 25°C. Bandgap reference temperature drift curvature correction and low dynamic impedance ensure stable reverse breakdown voltage accuracy over a wide range of operating temperatures and currents.

1.4.3 LM393

The LM393 is a dual differential comparator. This device consists of two independent voltage comparators that are designed to operate from a single power supply over a wide range of voltages. Operation from dual supplies also is possible as long as the difference between the two supplies is 2 to 36 V, and VCC is at least 1.5 V more positive than the input common-mode voltage. Current drain is independent of the supply voltage. The outputs can be connected to other open-collector outputs to achieve wired-AND relationships.

2 System Design Theory

This design uses a current sense amplifier for bi-directional high side current sensing. It measures the current flowing through a shunt resistor and also generates fast over-current fault alert in either direction. Figure 4 shows a schematic of the current-shunt approach. The circuit consists of three stages: the current sense amplifier, shunt voltage reference, and comparator.

2.1 *Selection of Sense Resistor*

Selecting the value of the current-sensing resistor is based primarily on two factors: the required accuracy of the current measurement and the allowable power dissipation across the current-sensing resistor. This reference design is used to generate alert signal for currents (in either direction) greater than a specified threshold using a sense resistor (R_{SENSE}). Other important parameters include resistance tolerance and temperature coefficients. The sense resistor is placed between the IBAT_HS+ and IBAT_HS– points (see Figure 4).

2.2 *Current-Sense Amplifier Stage*

Current-sense amplifier INA240A2PW (gain = 50) is used for current sensing. Connecting both pins, REF1 and REF2, together and to a reference (VREF) produces an output at the reference voltage when there is no differential input (see Figure 4). The output moves down from the reference voltage when the input is negative relative to the IN– pin and up when the input is positive relative to the IN– pin. VREF (= 1.2 V) is generated using shunt voltage reference, as explained in Section 2.3. The output is calculated by Equation 1:

$$OUT = VREF + G \times (IN+ - IN-) \quad (1)$$

$$IN+ - IN- = I \times R_{SENSE} \quad (2)$$

where

- I is the current through the sense resistor
- G is the gain of the current sense amplifier

For INA240A2PW, G = 50.

For different values of currents, the threshold voltages can be calculated using Equation 1 and Equation 2 by using different sense resistors (R_{SENSE}).

- For current = 100 A and R_{SENSE} = 0.33 mΩ, OUT = 2.85 V
- For current = –35 A and R_{SENSE} = 0.33 mΩ, OUT = 0.6225 V

A high threshold voltage (HTV) is used to detect overcurrent faults in forward direction, and a low threshold voltage (LTV) is used to detect overcurrent faults in reverse direction. This makes use of current sensing in either direction.

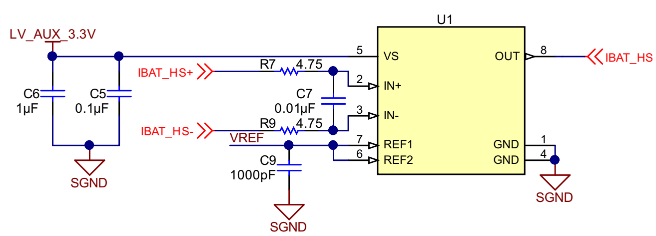


Figure 4. Current Sense Amplifier Stage

2.3 Voltage Reference Generation

The voltage reference used in the design is the LM4041-1.2, which generates voltage reference (V_{REF} = 1.2 V) for the INA240A2PW.A potential divider is used to generate threshold voltages (HTV and LTV) for the comparator for overcurrent detection in both directions (bidirectional current measurement). Because the output of the INA240 is internally divided by 2 using a potential divider, the threshold voltages are set to half of the calculated values (HTV = 2.85/2 V and LTV = 0.6225/2 V) as explained in Section 2.2. These comparison thresholds are configured through a resistive divider network with appropriate values of resistors chosen (see Figure 5), thus simplifying the circuit design while allowing for easy adjustments to the threshold when needed.

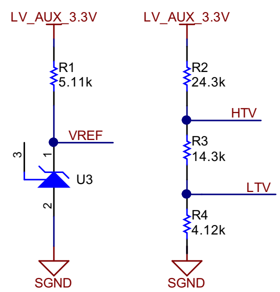


Figure 5. Voltage Reference Generation Stage

2.4 Comparator Stage

The LM393ADR dual differential comparator is used to make a window comparator in this TI Design. The output of the window comparator goes high if the output of the INA240 goes above the HTV threshold or goes below the LTV threshold.

The output of the INA240 is passed through potential divider and an RC network to avoid any high frequency glitches. It is then fed to the input of the window comparator. When the output of the INA240 goes above the HTV, it signifies that the input current has exceeded the overcurrent limit in the forward direction and when the INA240 output goes below the LTV, it signifies that the current has exceeded the overcurrent limit in the reverse direction. Correspondingly the window comparator output goes high. The comparator output can be connected to an MCU to generate an overcurrent interrupt.

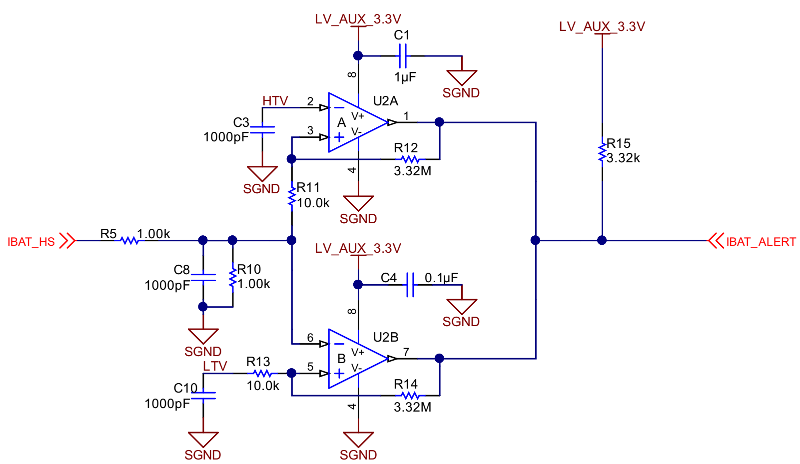


Figure 6. Comparator Stage

3 Getting Started Hardware

The TIDA-01141 PCB is a two layer design, with all the components placed on the top side and a ground plane on the bottom.

This sections shows the component placing on the top side and then goes in to the details of the test setup required.

3.1 TIDA-01141 PCB Overview

Figure 7 shows the top view of the TIDA-01141 PCB. The current sense amplifier INA240, the LM393 comparator and the LM4041 reference generator are marked. Figure 8 shows the bottom view of the TIDA-01141 PCB.

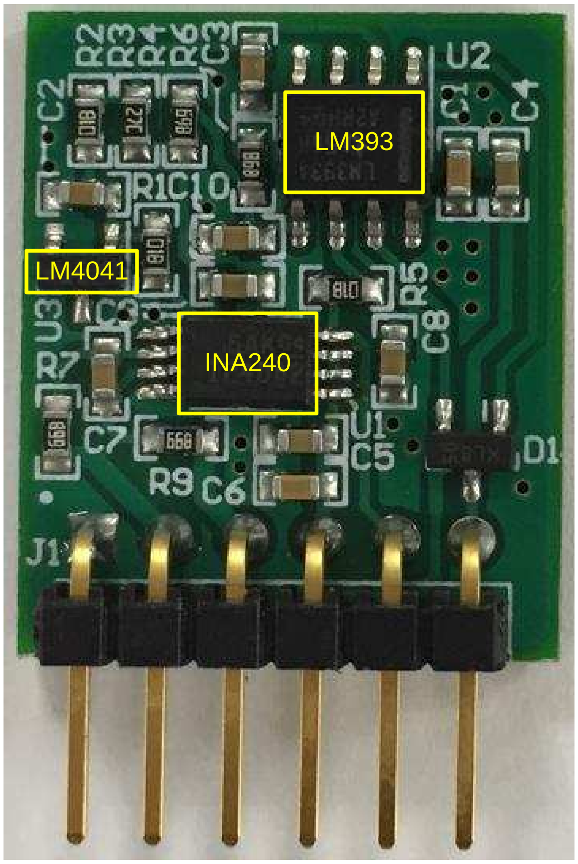


Figure 7. Top View of TIDA-01141

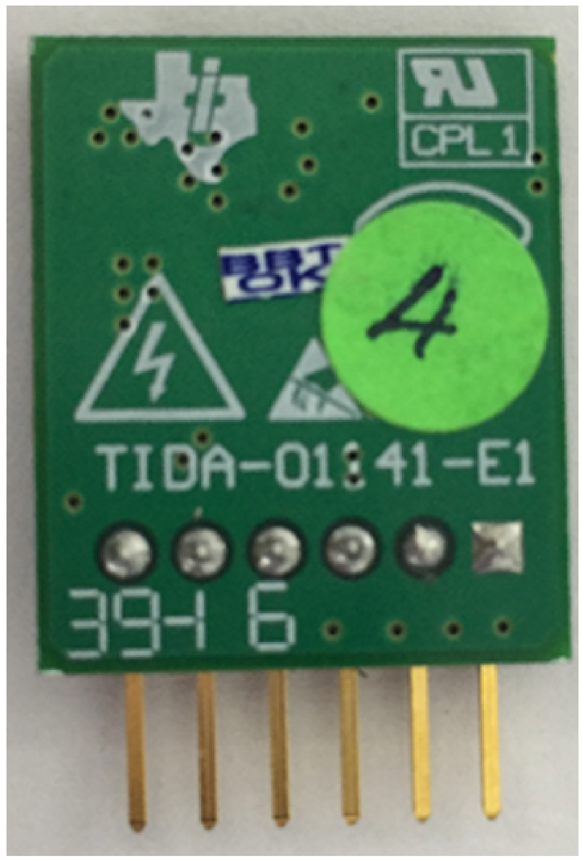


Figure 8. Bottom View of TIDA-01141

3.2 Connectors

Table 3 shows the pin functions for connector J1.

Table 3. Connector J1

PIN NO	PIN NAME	DESCRIPTION
1	SGND	Ground
2	IBAT_HS+	Connect to supply side of shunt resistor
3	IBAT_HS-	Connect to load side of shunt resistor
4	LV_AUX_3.3V	Low-voltage auxiliary 3.3 V
5	IBAT_HS	Output of INA240
6	IBAT_ALERT	Alert output

3.3 Test Setup

The TIDA-01141 has been tested using both DC and switching currents. The DC current tests have been performed to measure the DC performance parameters of the system like DC gain error and transient response test of the comparator. The switching current test has been performed using a half-bridge power stage so as to characterize the high frequency switching current waveform reproduction capability of the TIDA-01141.

3.3.1 DC Current Test

The DC test for measuring the DC accuracy of the system at extended temperature ranges requires the use of a thermal chamber. Figure 9 shows the setup for testing across the temperature range of –25°C to 85°C.

Figure 9. Test Setup for Testing Across Temperature Range

3.3.1.1 Test Equipment Needed to Validate Board for DC Current Test

- Thermal chamber
- 0- to 30-V, 0- to 25-A source
- 6½ digit multimeter from Agilent
- DC source: 0 to 10 V, 200 mA
- Sense resistor

3.3.1.2 Test Procedure

1. To test the design over a temperature range of –25°C to 85°C, keep the board inside the thermal chamber.
2. Set the 0- to 10-V auxiliary supply to 3.3 V with a current limit of 200 mA and connect it to J1 pin 4 (3.3 V) and pin 1 (SGND) of the TIDA-01141 board.
3. Connect a sense resistor of 1 mΩ between pins 2 and 3 of the TIDA-01141.
4. Connect the 0- to 30-V, 0- to 25-A source across the sense resistor.
5. Vary the input current in steps of 2 A over a range of –20 to 20 A.
6. Measure the voltages after every stage using a 6½ digit multimeter with the aid of averaging functionality.

3.3.2 Switching Current Test

In order to test the reproduction capability of the switching current waveform of the TIDA-01141 board, a half-bridge power stage is used. A top-level representation of the test setup is shown in Figure 10.

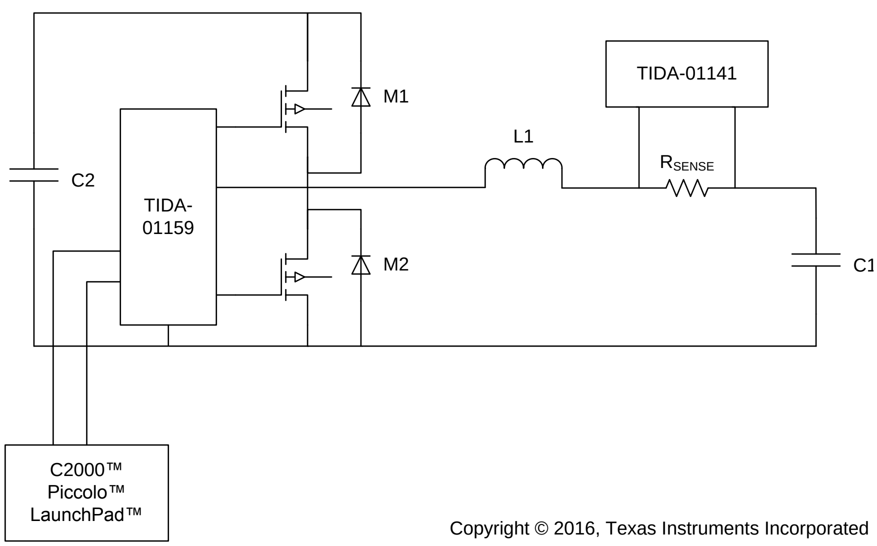


Figure 10. Test Setup

The TIDA-01141 is connected in this circuit to detect current in the half-bridge power stage. To power this half-power stage comprising of MOSFET M1 and M2, the inductor L1, and capacitors C1 and C2, in order to drive the half-bridge power stage, a half-bridge gate driver needs to be used. In the present test setup, the TIDA-01159 (Compact, Half-Bridge, Reinforced Isolated Gate Drive Reference Design) is used for implementing the gate drive functionality. The C2000™ Piccolo™ LaunchPad™ is used to generate two PWM signals for driving the half-bridge power stage. The PWM input signals are fed to the input pins of the TIDA-01159. To measure the current in the circuit, a sense resistor (R_{SENSE}) is placed between L1 and C1.

In this test case, the TIDA-01141 measure the voltage drop across the R_{SENSE}, which represents the inductor current, riding on a high common-mode voltage across the capacitor C1.

3.3.2.1 Test Equipment Needed to Validate Board

- DC source: 0- to 400-V DC, 2 A rated
- DC source: 0 to 10 V, 200 mA
- Four-channel digital oscilloscope
- Current probe: 0 to 30 A, 50 MHz
- Electronic or resistive load capable of working up to 400 V, 2 A
- C2000 LaunchPad or other source for generating complementary PWM
- TIDA-01159

3.3.2.2 Test Procedure

1. Set the 0- to 10-V auxiliary supply to 3.3 V with a current limit of 200 mA and connect it to J1 pin 4 (3.3 V) and pin 1 (SGND) of the TIDA-01141 board.
2. Set the 0- to 10-V auxiliary supply to 5 V with a current limit of 200 mA and connect it to J1 pin 3 (5 V)and pin 4 (SGND) of the TIDA-01159 board.
3. Connect the complementary PWM generated from a C2000 LaunchPad or any other source to J1 pin 1 and pin 2 of the TIDA-01159 board.
4. Connect the 0- to 400-V DC power supply to the half-bridge input.
5. Connect the electronic or resistive load to the half-bridge output.
6. Connect the sense resistor terminals to J1 pin 2 (IBAT_HS+) and pin 3 (IBAT_HS–) of the TIDA-01141.
7. Power up the 0- to 400-V DC power supply to 100 V.
8. Slowly increase the electronic or resistive load to about 100 mA.
9. Increase the 0- to 400-V DC power supply to 400 V.
10. Increase the electronic or resistive load to about 1 A.
11. Capture the switching waveforms in the oscilloscope.

4 Testing and Results

This section shows the test results for the TIDA-01141.

4.1 DC Accuracy Test

Figure 11 shows the calibrated accuracy of the current sensing system (between the output of INA240:IBAT_HS and Reference Voltage:VREF) for DC input current to the board across the temperature range. The 25-mV input corresponds to the 25-A DC current. For test conditions, see Section 3.3.1.

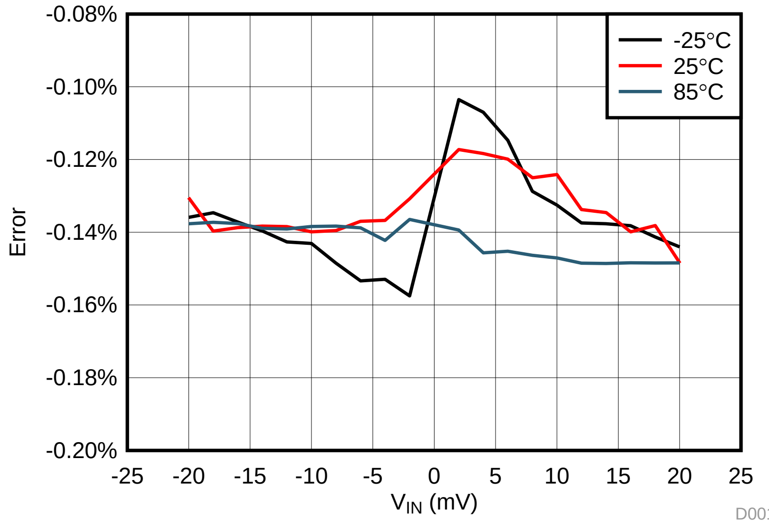


Figure 11. Accuracy of Current Sensing System

4.2 Reference Voltages

This section shows the different voltages generated using the voltage reference (LM4041) and potential divider network.

Figure 12 shows the reference voltage (V_{REF}) waveform, which shows a value of V_{REF} = 1.2020 V.

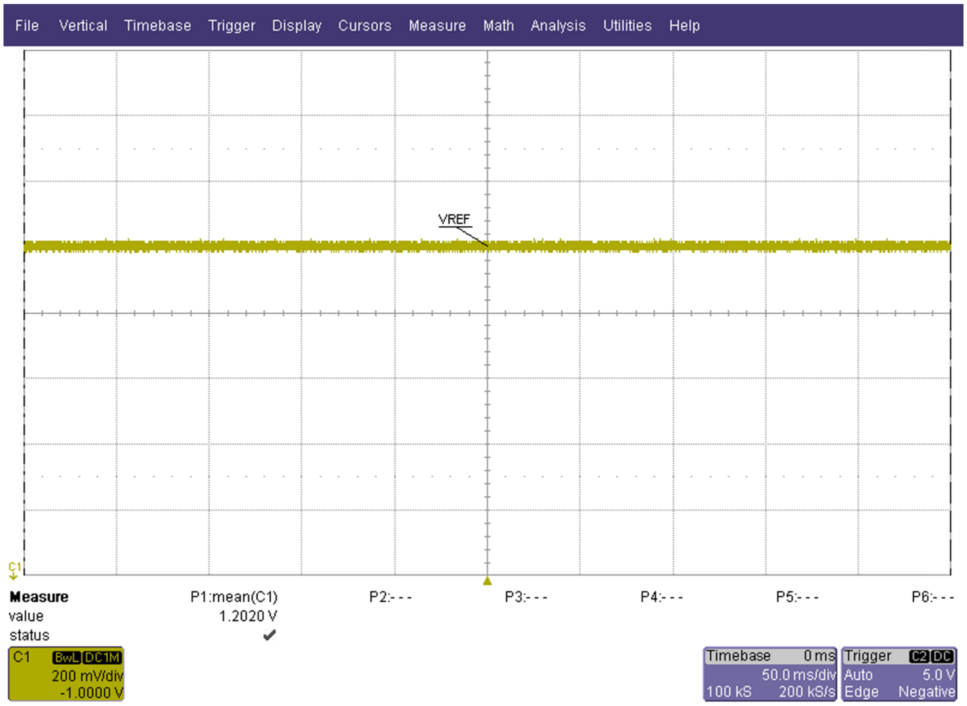


Figure 12. V_{REF} Voltage

Figure 13 shows the HTV waveform, which shows a value of V-HTV = 1.443 V. Figure 14 shows the LTV waveform, which shows a value of V-LTV = 0.298 V.

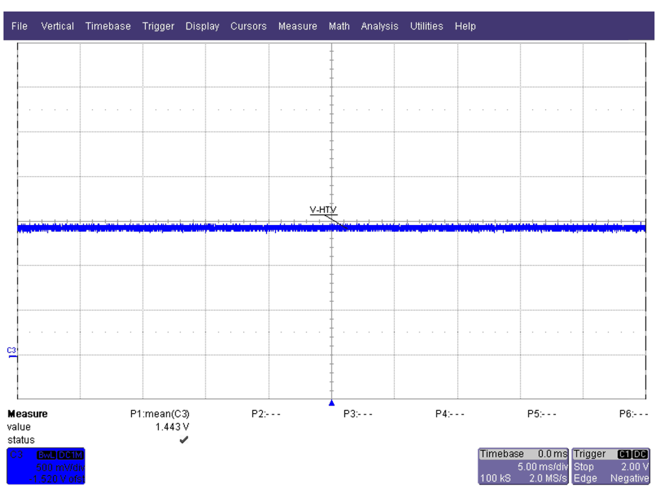


Figure 13. HTV Voltage

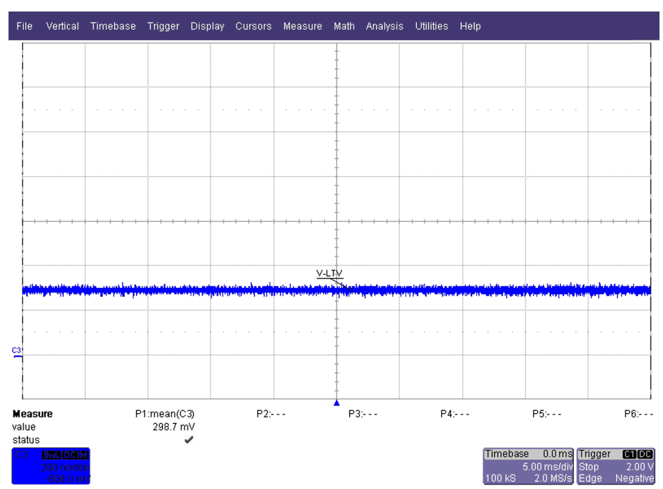


Figure 14. LTV Voltage

4.3 AC Switching Current Reproduction

Figure 15 and Figure 16 show the AC current reproduction capability of the TIDA-01141. This test was carried out using the half-bridge power stage, as explained in the Section 3.3.2.

The pink waveform shows the common-mode voltage, the purple waveform shows the switch-node voltage, the yellow waveform is the inductor current observed using current probe and the green waveform is the output of the INA240.

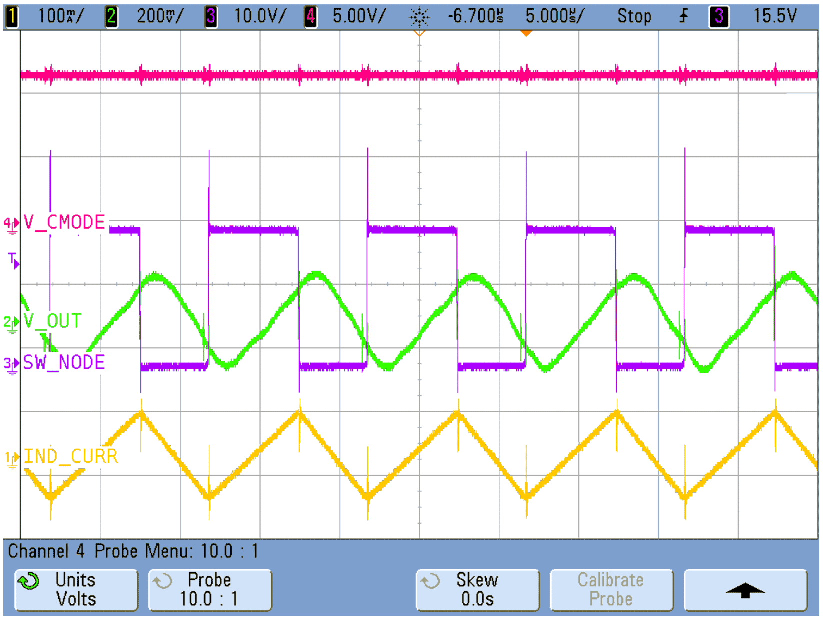


Figure 15. AC Switching Current Reproduction

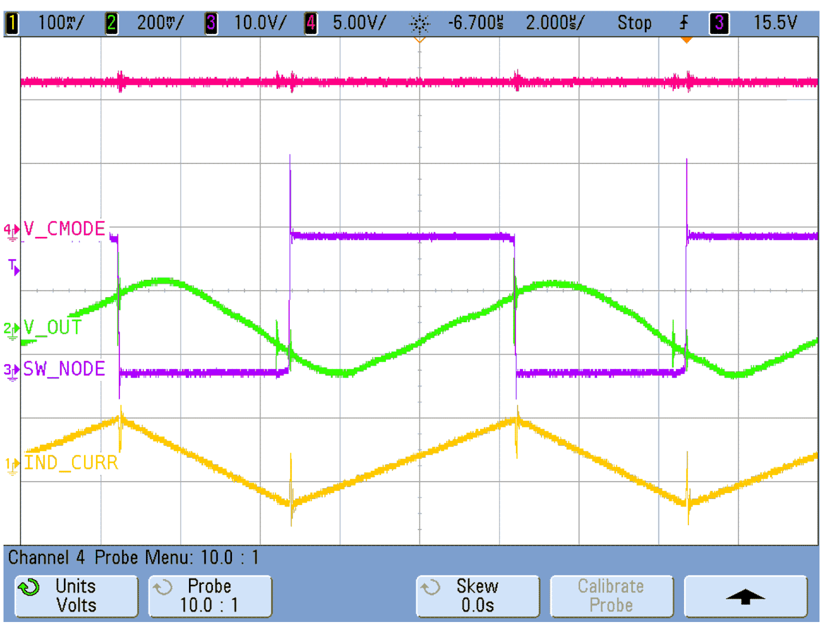


Figure 16. AC Switching Current Reproduction (Zoomed)

The half-bridge power stage was switched at 100 KHz. With a propagation delay of less than 1 µs, the inductor current waveform is reproduced effectively by the TIDA-01141.

4.4 Comparator Output

This section shows the comparator (LM393) output. Figure 17 shows that the comparator output changes once the output voltage of the current sense amplifier crosses the (V-HTV) threshold voltage.

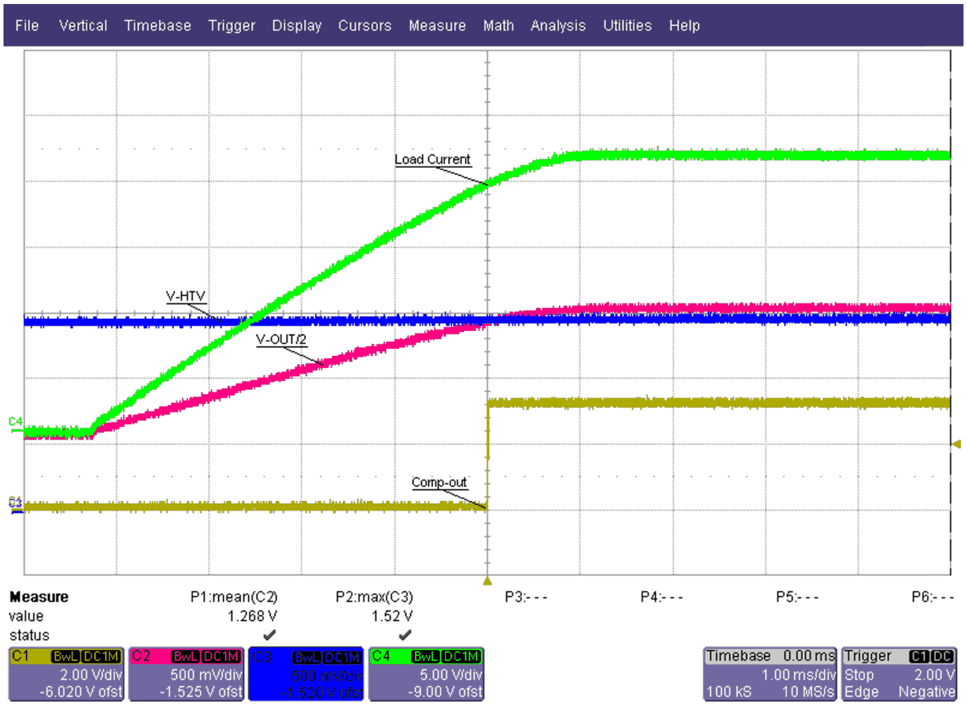


Figure 17. Comparator Output for Output Voltage Crossing V-HTV

Figure 18 shows that the comparator output changes once the output voltage of the current sense amplifier falls below the desired threshold voltage (V-HTV).

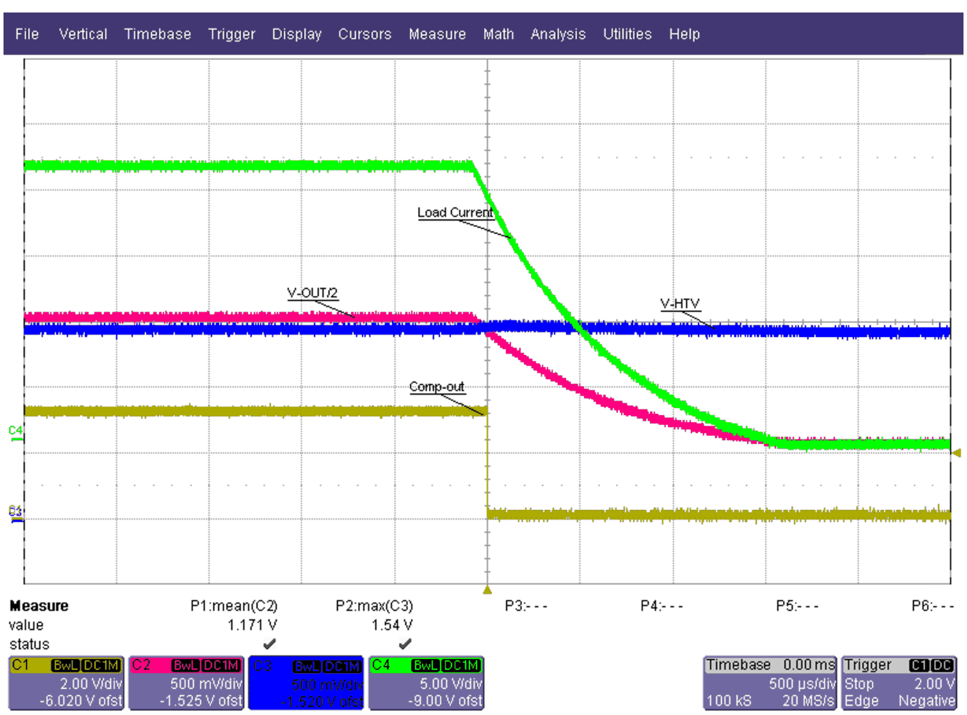


Figure 18. Comparator Output for Output Voltage Below V-HTV

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-01141.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01141.

5.3 PCB Layout Recommendations

In particular, follow these guidelines:

- The input pins of INA240, IN+ and IN–, must be connected as closely as possible to the shunt resistor to minimize any resistance in series with the shunt resistance. Poor routing of the current-sensing resistor commonly results in additional resistance present between the input pins. Given the very low ohmic value of the current resistor, any additional high-current carrying impedance causes significant measurement errors.
- For the device (INA240), place the power-supply bypass capacitor as close as possible to the supply and ground pins to compensate for noisy or high impedance power supplies.
- For the voltage reference (LM4041) used, place R1 close to the cathode. A 0.1-µF ceramic capacitor or larger is recommended at the output of the device. Place these external components as close to the device.
- For the comparator (LM393), to ensure that a stable power supply is maintained with minimum noise and glitches, add a bypass capacitor between the positive supply voltage and ground. Since a negative supply is not being used, a capacitor is *not* placed between the IC's GND pin and system ground.

5.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01141.

5.4 Altium Project

To download the Altium project files, see the design files at TIDA-01141.

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01141.

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01141.

6 References

1. Texas Instruments, *Compact, Half-Bridge, Reinforced Isolated Gate Drive Reference Design*, TIDA-01159 Design Guide (TIDUCG2)
2. Texas Instruments, *INA240EVM User's Guide* (SBOU177)
3. Texas Instruments, *Integrating the Current Sense Resistor*, Application Brief (SBOA170)
4. Texas Instruments, *High-Side Motor Current Monitoring for Over-Current Protection*, Application Brief (SBOA163)

6.1 Trademarks

All trademarks are the property of their respective owners.

7 About the Authors

NEHA NAIN is a systems engineer at Texas Instruments, where she is responsible for developing reference design solutions for the power delivery, industrial segment. Neha earned her bachelor of electrical and electronics engineering from the PES Institute of Technology (now PES University), Bangalore.

YAMINI SHARMA is a systems engineer at Texas Instruments, where she is responsible for developing reference design solutions for the power delivery, industrial segment. Yamini earned her bachelor of technology degree in electronics and communication from Delhi Technological University (formerly DCE), Delhi.

IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

Texas Instruments Incorporated ('TI") reference designs are solely intended to assist designers ("Designer(s)") who are developing systems that incorporate TI products. TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design.

TI's provision of reference designs and any other technical, applications or design advice, quality characterization, reliability data or other information or services does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such reference designs or other items.

TI reserves the right to make corrections, enhancements, improvements and other changes to its reference designs and other items.

Designer understands and agrees that Designer remains responsible for using its independent analysis, evaluation and judgment in designing Designer's systems and products, and has full and exclusive responsibility to assure the safety of its products and compliance of its products (and of all TI products used in or for such Designer's products) with all applicable regulations, laws and other applicable requirements. Designer represents that, with respect to its applications, it has all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. Designer agrees that prior to using or distributing any systems that include TI products, Designer will thoroughly test such systems and the functionality of such TI products as used in such systems. Designer may not use any TI products in life-critical medical equipment unless authorized officers of the parties have executed a special contract specifically governing such use. Life-critical medical equipment is medical equipment where failure of such equipment would cause serious bodily injury or death (e.g., life support, pacemakers, defibrillators, heart pumps, neurostimulators, and implantables). Such equipment includes, without limitation, all medical devices identified by the U.S. Food and Drug Administration as Class III devices and equivalent classifications outside the U.S.

Designers are authorized to use, copy and modify any individual TI reference design only in connection with the development of end products that include the TI product(s) identified in that reference design. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of the reference design or other items described above may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI REFERENCE DESIGNS AND OTHER ITEMS DESCRIBED ABOVE ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY DESIGNERS AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS AS DESCRIBED IN A TI REFERENCE DESIGN OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

TI's standard terms of sale for semiconductor products (http://www.ti.com/sc/docs/stdterms.htm) apply to the sale of packaged integrated circuit products. Additional terms may apply to the use or sale of other types of TI products and services.

Designer will fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of Designer's non-compliance with the terms and provisions of this Notice.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265