TI Designs: TIDA-01608
Isolated Current Sense Reference Design With Integrated Shunt Resistor and I²C Interface

Description

This verified design can accurately measure current on a bus that carries hundreds of volts. This design is targeted for solar and server applications due to their wide, high-voltage input range requirements. This design uses the INA260 current shunt monitor with integrated shunt resistor for current measurements, two P82B96 bidirectional buffers to facilitate I²C communication, and the ISOW7842 to allow isolated current measurements. The INA260 is limited by a common-mode voltage of 36 V; using the ISOW7842 allows the designer to float the INA260 side of the design to facilitate higher bus voltages.

Resources

TIDA-01608	Design Folder
INA260	Product Folder
ISOW7842	Product Folder
P82B96	Product Folder

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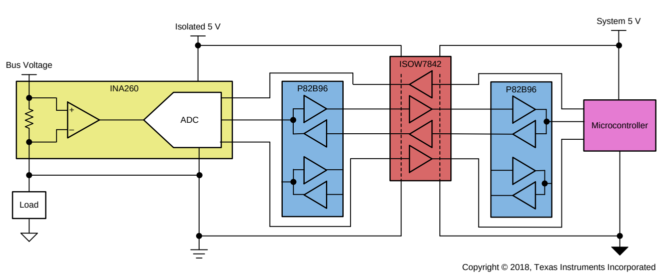
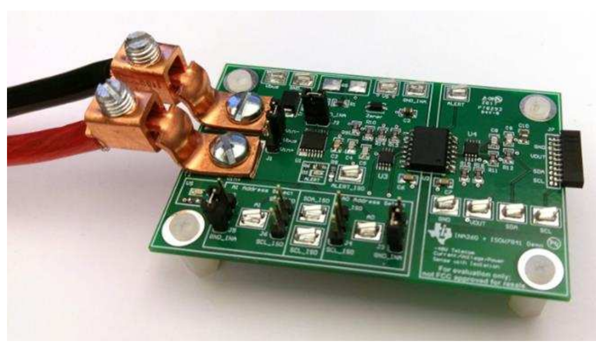
Features

- Current Measurement on High-Voltage Bus (±1 kV)
- Power Isolated
- I²C Compatibility
- Reinforced Digital I²C Isolation to Microcontroller
- 1% System Accuracy

Applications

- Solar Inverters
- Solar Combiner Boxes
- Server Power Supplies
- Server Infrastructure





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1 System Description

At the time of this writing, TI current shunt monitors can only measure high-side configured bus voltages up to 80 V and down to –16 V. Measurement of a bus voltage beyond these ranges requires a difference amplifier solution, low-side implementation, or isolated amplifiers. The goal of this reference design is to provide a solution to measure current and power on high-voltage buses with high accuracy without the need for more expensive isolated topologies. Some of the applications that can benefit from this design are solar energy and servers.

With the rapid worldwide market growth in solar energy, innovation continues to drive inverter design. Modern inverters must have a proven reliability across various grid types, while increasing conversion efficiency and integrating new safety and control features. Photovoltaic (PV) installations tied to the grid are usually built with arrays of modules connected in series to string inverters. For large-array installations with a capacity greater than 10 kW, a solar central inverter performs the conversion of the variable DC power of the PV cells to AC power. Multiple string inputs are combined at the DC input of the central inverter. After the DC combination, each combined input proceeds through voltage and current sensing subsystems, individual DC/DC converters, and individual DC/AC converters. For PV arrays with a power capacity greater than 50 kW, combining the PV strings into a high-voltage DC bus before the inverter is necessary. This system is known as a solar combiner box. This reference design lets designers evaluate the current on this high-voltage DC bus, and it can be used as reference for solar combiner box applications.

A server computer is a computing system designated to run a specific application or applications for extended periods of time and often with minimal human interference. Although servers can be built from commodity computer components, dedicated servers use specialized hardware for optimal reliability. Special, redundant, uninterruptible power supplies are required to ensure no loss of data is experienced during a power failure. The isolated DC/DC power stage of the server power supply is the main power converter stage. This stage is required to convert the high-voltage DC bus obtained at the output of power factor correction (PFC) to the usable 12- or 48-V (or other) output. This power stage is capable of handling a wide input range and delivering consistent high power at a high efficiency. This reference design assists designers with evaluating the power efficiency of their application.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	DESCRIPTION	SPECIFICATIONS
Bus voltage	Working bus voltage range	±1 kV
Isolation	Isolation capability range	≥ 1 kV
Measurements	What the system can measure and report	Shunt voltage and current
Communication	System communication protocol	I^2C compatible
Operating temperature	–40°C to 85°C (limited by P82B96 operating range)	–40°C to 85°C (limited by P82B96 operating range)
INA260 accuracy	Current shunt monitor accuracy	±1% error

2 System Overview

2.1 Block Diagram

shows the basic block diagram of the design, which comprises four stages. The first stage (yellow) uses a current shunt monitor, INA260, to measure the load current. The second stage (red) uses a digital isolator, ISOW7842, to provide the required 1-kV working voltage isolation between the current sensing circuit and the MCU. The third stage (blue) incorporates two bus buffer devices, P82B96. These devices support bidirectional data transfer between the I^2C bus at different voltage levels. The fourth stage (pink) uses the TI SM-USB-DIG Platform and INA260EVM software to display the data collected by the INA260 device.

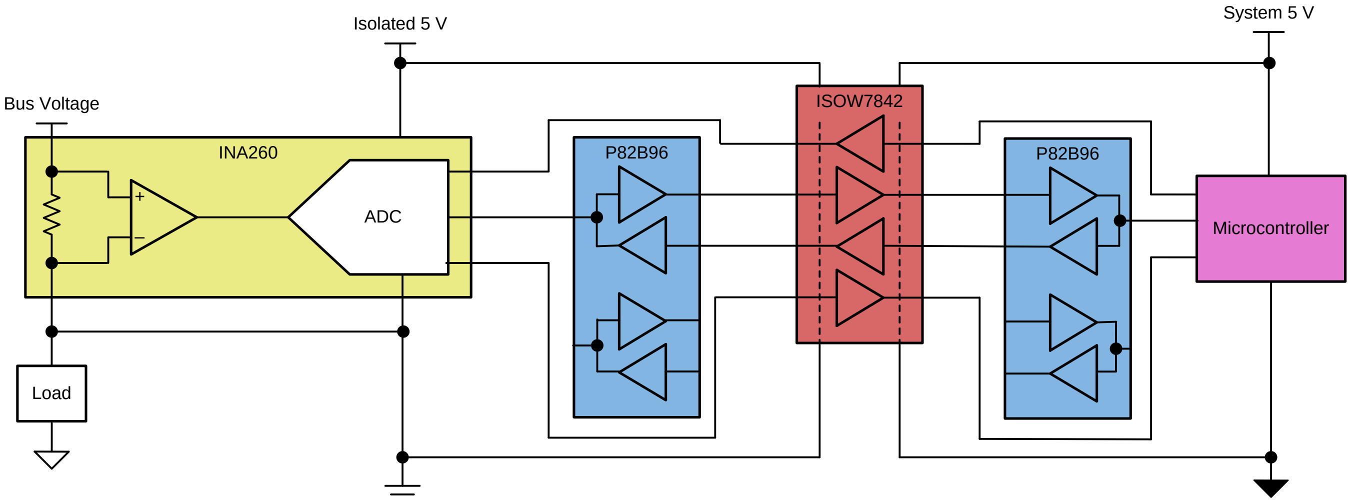

Figure 1. TIDA-01068 Block Diagram

2.2 Highlighted Products

2.2.1 INA260

The INA260 is a digital-output, current, power, and voltage monitor with an I^2C- and SMBus™-compatible interface with an integrated precision shunt resistor. This monitor enables high-accuracy current and power measurements and overcurrent detection at common-mode voltages that can vary from 0 V to 36 V, independent of the supply voltage. The device is a bidirectional, low- or high-side, current-shunt monitor that measures current flowing through the internal current-sensing resistor. The integration of the precision current-sensing resistor provides calibration-equivalent measurement accuracy with ultra-low temperature drift performance and ensures that an optimized Kelvin layout for the sensing resistor is always obtained. The INA260 features up to 16 programmable addresses on the I^2C-compatible interface. The digital interface allows programmable alert thresholds, analog-to-digital converter (ADC) conversion times, and averaging. To facilitate ease of use, an internal multiplier enables direct readouts of current in amperes and power in watts. The device operates from a single 2.7-V to 5.5-V supply, drawing 310 µA (typical) of supply current. The INA260 is specified over the operating temperature range between –40°C and +125°C and is available in the 16-pin TSSOP package.

2.2.2 ISOW7842

The ISOW784x is a family of high-performance, quad-channel reinforced digital isolators with an integrated high-efficiency power converter. The integrated DC/DC converter provides up to 650 mW of isolated power at high efficiency and can be configured for various input and output voltage configurations. These devices eliminate the need for a separate isolated power supply in space-constrained isolated designs. The ISOW784x family of devices provide high electromagnetic immunity and low emissions while isolating CMOS or LVCMOS digital I/Os. The signal-isolation channel has a logic input and output buffer separated by a silicon dioxide (SiO_2) insulation barrier, whereas, power isolation uses on-chip transformers separated by thin film polymer as insulating material. Various configurations of forward and reverse channels are available. If the input signal is lost, the default output is high for the ISOW784x devices and low for the devices with the F suffix. These devices help prevent noise currents on a data bus or other circuits from entering the local ground and interfering with or damaging sensitive circuitry. Through innovative chip design and layout techniques, electromagnetic compatibility of the ISOW784x family of devices has been significantly enhanced to ease system-level electrostatic discharge (ESD), electrical fast transient (EFT), surge, and emissions compliance. The high efficiency of the power converter allows operation at a higher ambient temperature. The ISOW784x family of devices is available in a 16-pin SOIC wide-body (SOIC-WB) DWE package.

2.2.3 P82B96

The P82B96 device is a bus buffer that supports bidirectional data transfer between an I^{2}C bus and a range of other bus configurations with different voltage and current levels. One of the advantages of the P82B96 is that it supports longer cables or traces and allows for more devices per I^{2}C bus because it can isolate bus capacitance such that the total loading (devices and trace lengths) of the new bus or remote I^{2}C nodes are not apparent to other I^{2}C buses (or nodes). The restrictions on the number of I^{2}C devices in a system due to capacitance, or the physical separation between them, are greatly improved.

2.3 System Design Theory

2.3.1 First Stage: Current Sensing

This reference design requires the use of a current shunt monitor with a wide common-mode range; high accuracy; ability to report current; and the capability to perform I^{2}C interface communication. The chosen current shunt monitor for this application is INA260. This device not only has the accuracy to achieve the design goals, but also features a precise, low-drift, 2-mΩ internal current-sensing resistor to allow for precision measurements. The integrated current-sensing resistor ensures measurement stability over temperature as well as simplifying printed-circuit board (PCB) layout difficulties common in high-precision, current-sensing measurements. The INA260 is internally calibrated to ensure that the current-sensing resistor and current-sensing amplifier are both precisely matched to one another. For this application, the shunt resistor is on the high side of the load, and directly measures the current flowing into the load from each input.

The INA260 functions as a digital current and power monitor when the circuit is designed such that the voltage on the bus is measured with respect to load ground, because load current × bus voltage = power. However, the INA260 silicon only supports 36 V on the bus voltage input; so, the device cannot directly measure higher voltages for the power calculation. A resistor divider can occasionally be used to obtain a divided-down bus voltage measurement (as is the case in TIDA-00313) so that the power can be calculated and linearly scaled back up by the I^{2}C master microprocessor. An example of operation would be measuring a 100-V bus rail, divided down by a series of 300-kΩ and 100-kΩ resistors to effectively reduce the bus voltage by a factor of 4, so that the 100-V rail would measure as 25 V, which is beneath the 36-V silicon limit.

Use of this resistor divider for measurement also requires that the integrated shunt resistor be placed in the low-side configuration, wherein the INA260 device ground and the load ground are connected, and the shunt is between the load and the ground. For reference, a high-side-connected shunt would be placed between the bus rail and the load. There are reasons to do both high- and low-side implementations and one of the drawbacks of using a low-side configuration is that the load is not directly grounded. This reference design uses a low-side implementation with a key adjustment—the shunt is placed on the high side of the INA260 and the device ground is attached to IN–, between the shunt and the load. Normally, this configuration does not work because the system grounds are eventually connected, and at that point, both sides of the load would be shorted to the same node and the circuit would not function. In this design, adding the ISOW7842 creates an isolation barrier with a generated, isolated-supply voltage to power the INA260 device. Because of this isolation, the device ground and load ground are no longer connected together elsewhere on the board, and the circuit continues to operate as expected.

2.3.2 Second Stage: Digital Isolation

This reference design requires that a device provide up to 1.0-kV isolation between the current sense amplifier and the MCU because the INA260 bus voltage is limited from 0 V to 36 V. The chosen digital isolator is ISOW7842. Using the ISOW7842 allows the designer to essentially float the INA260 side of the design, which facilitates isolated current measurement. Because the supply for the INA260 is generated by the ISOW7842, the circuit is not that different from a digital multimeter being powered by a battery, which can be inserted into a circuit to measure current at various voltage levels regardless of the system ground. The isolation of the ISOW7842 is not infinite, but rather limited by the size of the package and the breakdown voltage of air. A good general rule is that, for each millimeter of separation, the gap can isolate a transient voltage of 1 kV. This fact means that the air in a 1-mm gap between two conductors breaks down and conducts when the difference in potentials is 1 kV. A 2-mm gap requires a 2-kV surge to break down, and so forth. The minimum dimensions of the ISOW7842 package allow for, at most, a 8-mm gap; so this circuit can survive a surge of up to 8 kV.

Transient survivability and working voltages are not the same; the working voltage is substantially lower than the allowable transient. A circuit must be designed with attention to both creepage and clearance distances to provide good isolation. Clearance is essentially the shortest distance through the air between two conductors. Creepage is more planar because it is the shortest distance along the surface of a solid, insulating material (like a PCB), between two conductors. The creepage will always be equal to or less than the clearance, depending on the packaging of components in a circuit. Creepage can be artificially increased by adding a slot or hole between the conductors, which creates a longer path along the surface for current to travel. However, the clearance can only be increased by adding more non-air, insulating material between the conductors. This design provides 8 mm of clearance. For more information on this PCB layout, see Section 5.3.

2.3.3 Third Stage: I^{2}C Buffers

This design requires a bus buffer that supports bidirectional data transfer between the MCU (and I^{2}C master) and the ISOW7842 and between the INA260 and the ISOW7842. The P82B96 is the device chosen for this task. The device operates from 2 V to 15 V and provides an excellent way to convert the bidirectional SDA signal into two opposing unidirectional signals to transmit data across the ISOW7842 barrier device. The SCL line is unidirectional and is sourced only by the I^{2}C master, and the INA260 ALERT signal is sourced only by the INA260, so additional bidirectional signal path conversions are not required, which is why the second signal converter on the P82B96 is not used in this design. The SCL and ALERT signals transmit across the barrier device directly.

2.3.4 Fourth Stage: TI SM-USB-DIG Platform and INA260EVM Software

The SM-USB-DIG platform is a general-purpose data acquisition system that is used on several different TI evaluation modules and designs. The primary control device of the SM-USB-DIG platform is the TUSB3210. The TUSB3210 is an 8052 MCU that has a built-in USB interface. The MCU receives information from the host computer that it interprets into power, I^{2}C, serial peripheral interface (SPI), and other digital input and output (I/O) patterns. During the digital I/O transaction, the MCU reads the response of any device connected to the I/O interface. The response from the device is sent back to the PC, where it is interpreted by the host computer. The software used to read the current measurements is the INA260EVM software.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The contents of the reference design kit are as follows:

- TIDA-01608 board
- USB SM-DIG Platform PCB
- USB extender cable

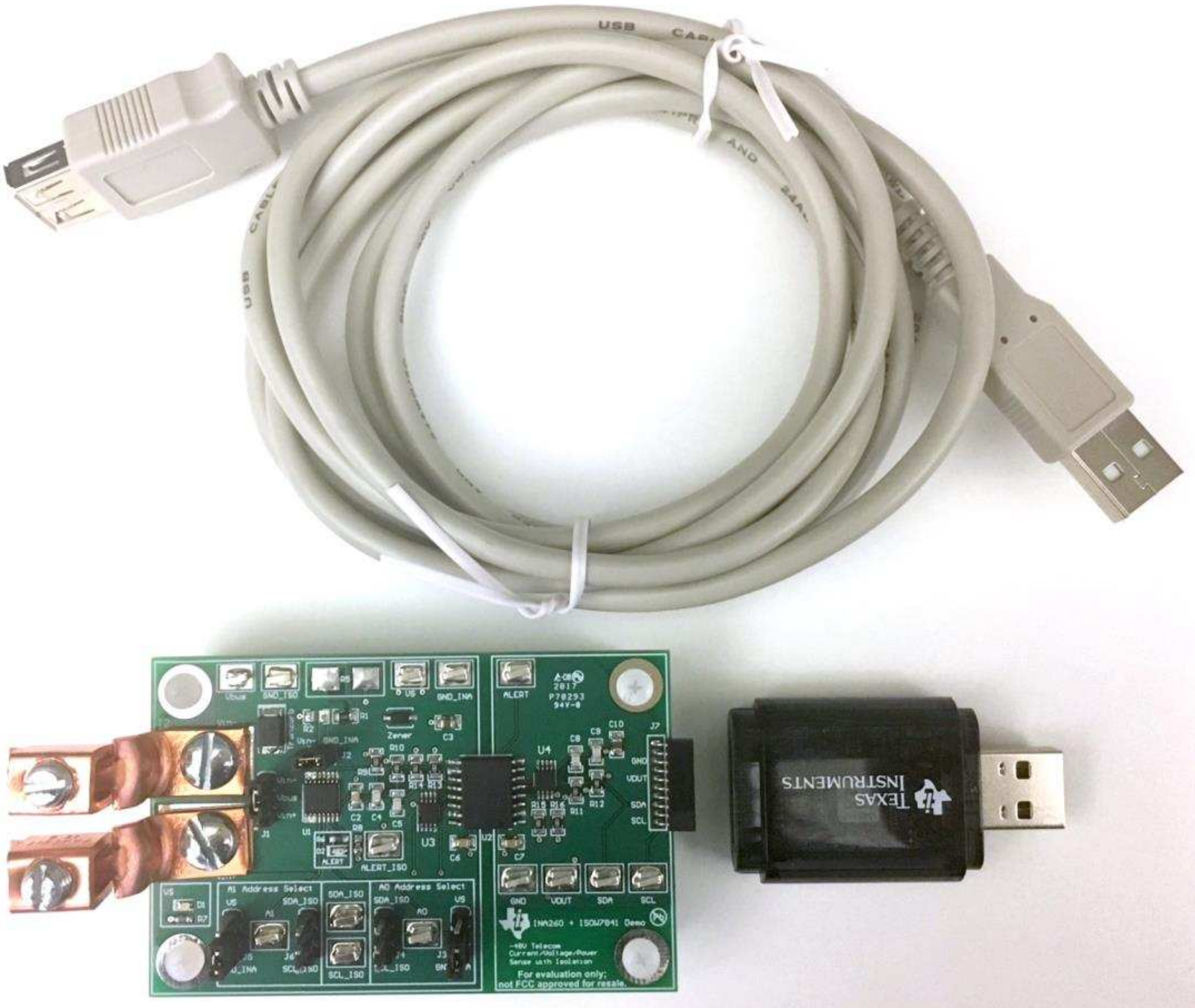

Figure 2. Required Hardware for TIDA-01608 Evaluation

3.1.2 Software

The INA260EVM GUI and TI SM-USB-DIG are used to interpret the data output from the board. For more information on how to use the INA260EVM software, see *INA260EVM-PDK User's Guide*.

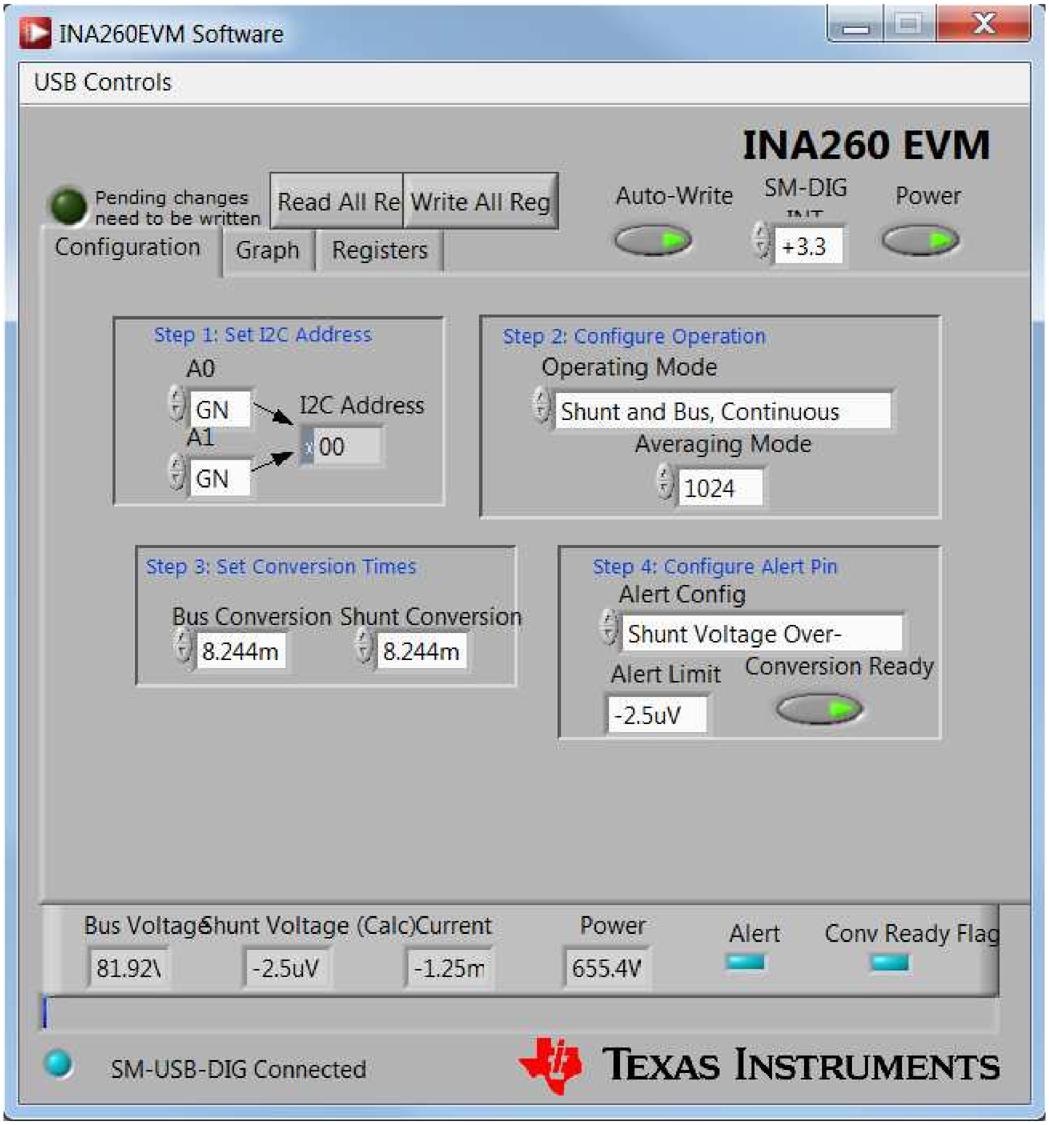

Figure 3. INA260EVM GUI

4 Testing and Results

4.1 Test Setup

A power supply (E3612A) and a variable digital load (PLZ334W) were used to simulate the DC bus connected to a load. The DC voltage was connected to the T1 terminal (VIN+) and the variable digital load was connected to the T2 terminal (VIN–) of the TIDA-01608 board. The TI SM-USB-DIG provides the 5-V supply voltage to power the TIDA-01608 board. The INA260EVM GUI software is used to collect the sensed current data and a DC multimeter is used to monitor the DC voltage corresponding to the voltage sense measurement. Figure 4 shows a block diagram of the test setup. Due to limitations of the equipment, the full ±1-kV capable range of this design was not tested; a range from 1 V to 120 V was used for concept validation.

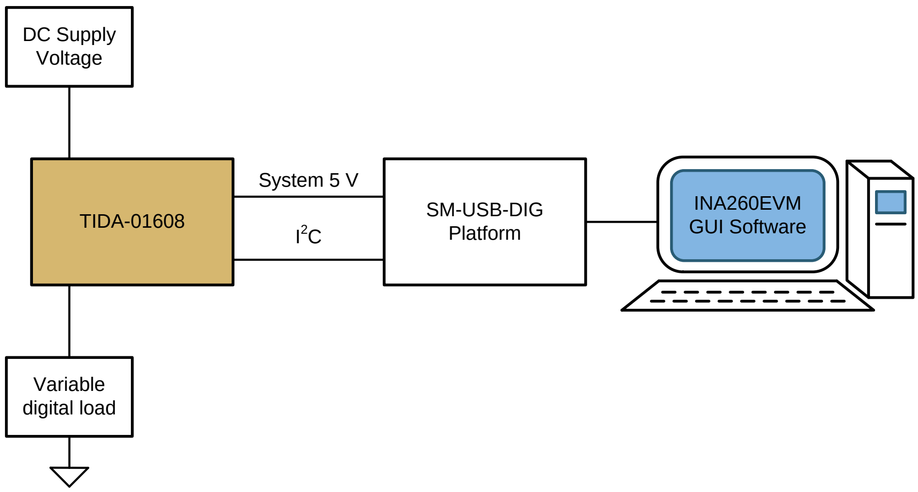

Figure 4. Test Setup

4.2 Test Results

4.2.1 Data Collected With Common-Mode Voltage V_{CM} = 60 V and Load Current I_L = 50 mA to 500 mA

For this test, the data was collected by sweeping the load current from 0 mA to 500 mA with a constant supply voltage of 60 V. The load current value was compared to the current value read by the INA260EVM software. Table 2 shows the collected data.

Table 2. V_{CM} = 60 V, Load Current I_L = 50 mA to 500 mA

VOLTAGE (V)	NOMINAL CURRENT (A)	ACTUAL CURRENT (A)	CURRENT MEASURED GUI (A)	ERROR (%)
60	0.050	0.0540	0.0538	0.4630
60	0.100	0.1020	0.1023	0.2941
60	0.150	0.1530	0.1525	0.3268
60	0.200	0.2040	0.2034	0.2941
60	0.250	0.2540	0.2533	0.2756
60	0.300	0.3040	0.3032	0.2632
60	0.350	0.3540	0.3530	0.2825
60	0.400	0.4040	0.4029	0.2723
60	0.450	0.4560	0.4548	0.2632
60	0.500	0.5000	0.5012	0.2400

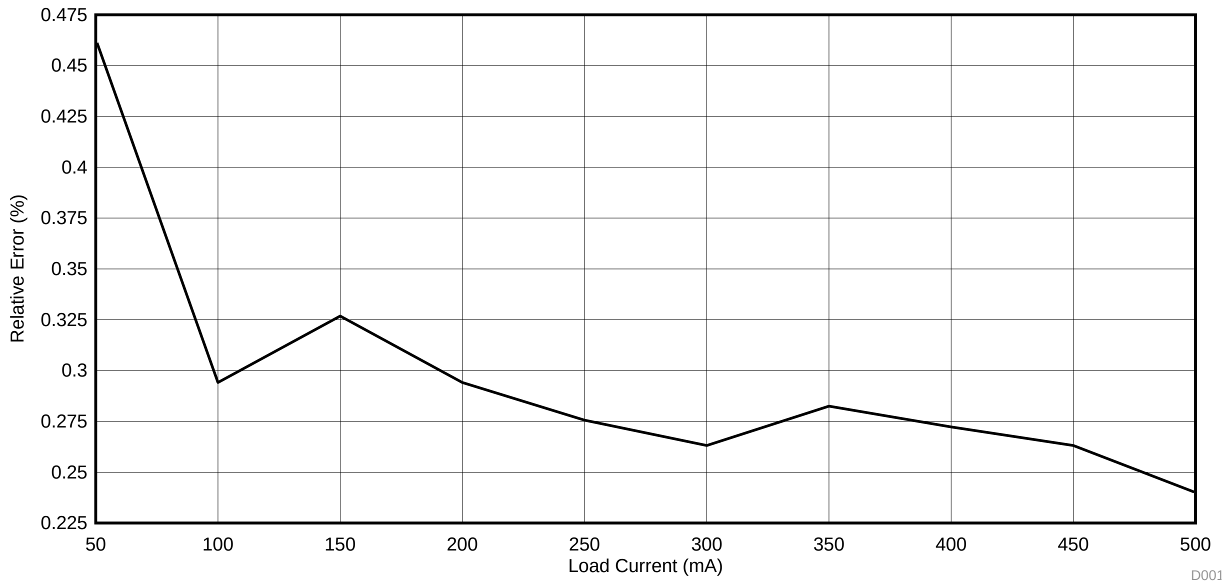

Figure 5. Measured Relative Error With V_{CM} = 60V, Load Current I_L = 50 mA to 500 mA

4.2.2 Data Collected With Common-Mode Voltage V_{CM} = 120 V and Load current I_L = 50 mA to 250 mA

For this test, the data was collected by sweeping the load current from 0 mA to 250 mA with a constant supply voltage of 120 V. The load current value was compared to the current value read by the INA260EVM software. Table 3 shows the collected data.

Table 3. V_{CM} = 120 V, Load Current I_L = 50 mA to 250 mA

VOLTAGE (V)	NOMINAL CURRENT (A)	ACTUAL CURRENT (A)	CURRENT MEASURED GUI (A)	ERROR (%)
120	0.025	0.0260	0.02625	0.9615
120	0.050	0.0540	0.05375	0.4630
120	0.075	0.07625	0.07625	0.3289
120	0.100	0.1040	0.10380	0.1923
120	0.125	0.1260	0.12500	0.7937
120	0.150	0.1490	0.14870	0.2013
120	0.175	0.176	0.17620	0.1136
120	0.200	0.2030	0.20360	0.29557
120	0.225	0.2260	0.22630	0.1327
120	0.250	0.2490	0.24870	0.1205

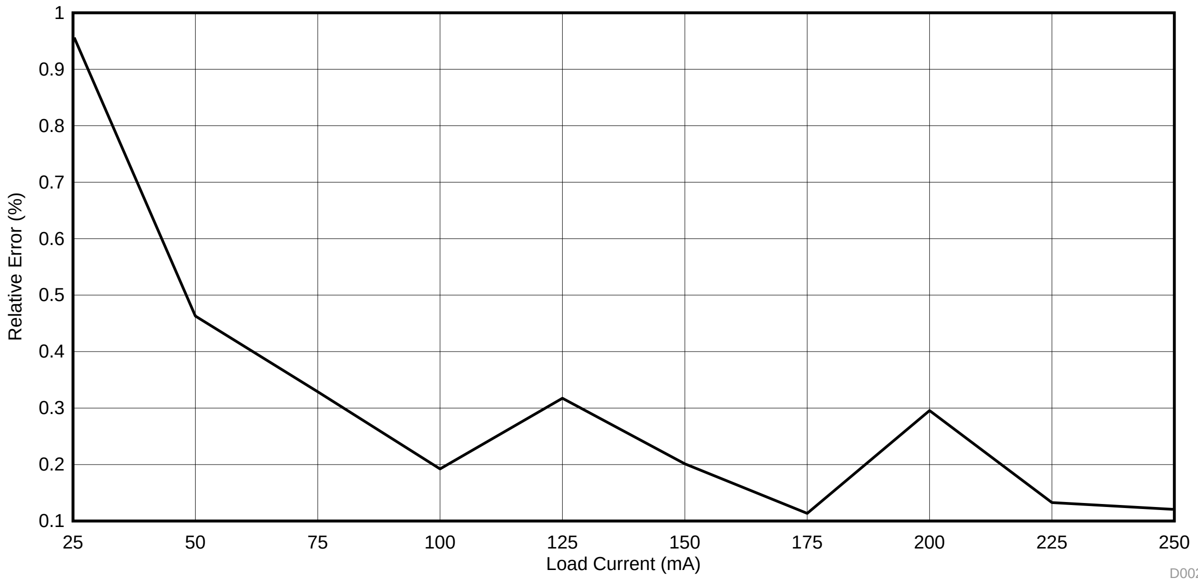

Figure 6. Measured Relative Error With V_{CM} = 120 V, Load Current I_L = 50 mA to 250 mA

4.2.3 Data Collected With Common-Mode Voltage V_{CM} = 1 V and Load Current I_L = 1 A to 15 A

The data was collected by sweeping the load current from 0 A to 15 A with a constant supply voltage of 1 V. The load current value was compared to the current value read by the INA260EVM software. Table 4 shows the collected data.

Table 4. V_{CM} = 1 V and Load Current I_L = 1 A to 15 A

VOLTAGE (V)	NOMINAL CURRENT (A)	ACTUAL CURRENT (A)	CURRENT MEASURED GUI (A)	ERROR (%)
1	1	1.00300	1.002	0.0997
1	2	2.00500	2.007	0.0998
1	3	3.00040	2.998	0.0800
1	4	3.99992	3.996	0.0980
1	5	4.9998	4.995	0.0960
1	6	6.00000	5.994	0.1000
1	7	7.00000	6.994	0.0857
1	8	8.00000	7.993	0.0875
1	9	9.00020	8.992	0.0911
1	10	10.00080	9.992	0.0880
1	11	11.00100	10.99	0.0100
1	12	12.00100	11.99	0.0917
1	13	13.00200	12.99	0.0923
1	14	14.00260	13.99	0.0900
1	15	15.00380	14.98	0.1920

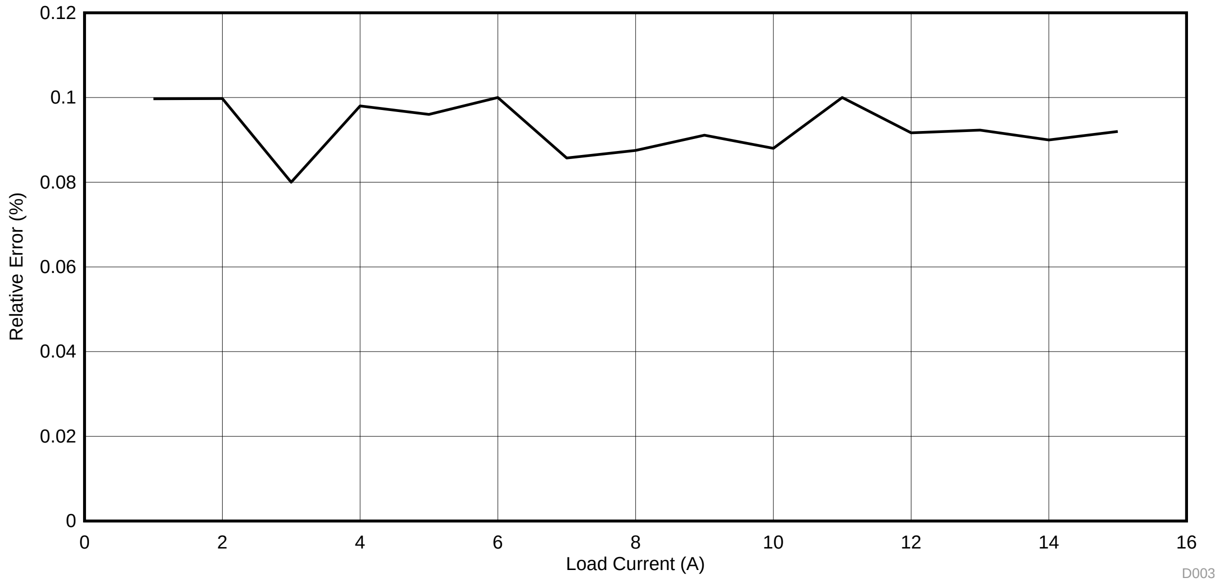

Figure 7. Measured Relative Error With V_{CM} = 1 V and Load Current I_L = 1 A to 15 A

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-01608 .

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01608 .

5.3 PCB Layout Recommendations

Design for isolation requires attention to the clearance between low and high voltages on the PCB. With this layout, the ISOW7842 straddles the isolation barrier. The pins on the body of the package are the closest conductors with the highest voltage potential difference, which is 8 mm. The breakdown of air is 1 kV/mm, so for high-voltage surges, the isolation level is 8 kV. For continuous working voltage levels, the maximum potential difference with an 8-mm separation is only 1414 V at DC.

If the planes under the ISOW7842 device come closer together than the pins, then this voltage level is reduced. For example, a 3-mm gap would only survive a surge of 3 kV and would only support a continuous working voltage of 424 V at DC.

5.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01608 .

5.4 Altium Project

To download the Altium project files, see the design files at TIDA-01608 .

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01608 .

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01608 .

6 Software Files

To download the software files, see the design files at TIDA-01608 .

7 Related Documentation

1. Texas Instruments, *–48-V Telecom Current, Voltage, and Power Sense With Isolation Reference Design*
2. Texas Instruments, *Reference Design for 1200-V, Isolated, I2C, High-Side Current Sensing*
3. Texas Instruments, *600-V Unidirectional Curr/Volt/Power Monitoring for Solar Smart Combiner Box*
4. Texas Instruments, *INA260EVM-PDK User's Guide*

7.1 Trademarks

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8 About the Authors

JASON BRIDGMON, MAYRIM VERDEJO, and **MITCH MORSE** are Applications Engineers at Texas Instruments (TI), where they work primarily with current and magnetic sensing products. Jason received bachelor of science degrees in electrical and computer engineering at the University of Denver. Mayrim received her bachelor of science degree from the University of Puerto Rico, Mayagüez with an emphasis on digital signal processing. Mitch received his bachelor's degree from Utah State University in Electrical Engineering.

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