TI Designs: TIDA-03040
Automotive Shunt-Based ±500-A Precision Current Sensing Reference Design

Description
The TIDA-03040 design provides an accuracy of 0.2% FSR over a –40°C to 125°C temperature range. Precision current sensing is essential in several applications in automotive such as battery management systems, motor currents, and so on. Generally in these applications, the poor accuracy is because of non-linearity, temperature drift, and shunt tolerances; this TI Design solves these problems by using TI’s current shunt monitors and signal conditioners (INA240, PGA400-Q1).

Features
- Accuracy of 0.2% FSR Over Temperature (–40°C to 125°C)
- Suitable for ±500-A, High- and Low-Side Current Sensing
- Compensated for Temperature and Non-Linearity (Second Order Temperature and Linearity Compensation Algorithm)
- Protection Against Harness Faults (Overvoltage, Reverse Polarity, Input/Output Signal Protection)
- Electromagnetic Interference (EMI) Protection

Resources
- TIDA-03040 Design Folder
- PGA400-Q1 Product Folder
- INA240 Product Folder
- PGA400-Q1 EVM Product Folder

Features
- Accuracy of 0.2% FSR Over Temperature (–40°C to 125°C)
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Applications
- 48-V or 12-V Battery Management Systems
- Motor Control Systems

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1 System Description

Vehicles are becoming more electrified—not just electric vehicles or hybrid-electric vehicles, but even gasoline and diesel powered machines. It becomes more critical to accurately monitor the current consumed to ensure performance as well as long-term reliability. Current sensing is critical for essential operations such as motor control, DC/DC, battery monitoring, and so on. The performance of any current sensor solution mainly depends on the device specifications such as accuracy, bandwidth, linearity, and precision. Designing a system that satisfies all the required specification is a challenging task. This TI Design shows how to handle the following parameters: accuracy, linearity, and precision.

Current can be measured in many ways such as Faraday’s induction law, Ohm’s law, Lorentz force law, magneto-resistance effect, and the magnetic saturation. This reference design is based on Ohm’s law (shunt current sensing). Each technology has its own advantages and disadvantages, depending on the place of use every customer has his or her own preference of which topology to choose. When designing the current sensor, it is essential to choose where exactly current is being measured, its current measurement range, its low side or high side, and whether it is uni- or bidirectional; the topology and design can be defined based on these parameters. By considering these parameters, the present reference design topology is defined as follows:

- Measurement range: ±500 A, implies bidirectional
- Low side or high side (configurable)
- Accuracy: 0.2% FSR
- Temperature range: –40°C to 125°C

A ±500-A current is made to pass through the 100-μΩ shunt. Small amounts of tiny voltage drops appear across the 100-μΩ shunt. Using TI’s current shunt monitor (INA240 (1)), this small amount of voltage drop is measured and given to the PGA400-Q1 for linearity and compensation algorithms. The PGA400-Q1 gives ratiometric analog output (0.5 to 4.5 V). Figure 1 shows the conceptual block diagram and signal definitions.

As shown in Figure 1, across the 100-μΩ shunt, ±500 A of current will generate –50 to 50 mV. The INA240 has a reference voltage of 2.5 V (generated from PGA400-Q1 DAC), which implies it gives an output voltage in between 1.5 to 3.5 V. The PGA400-Q1 inputs cannot directly accept this voltage; in order to match the INA240 and PGA400-Q1 signal levels, an attenuator is constructed with 0.1% tolerance resistors. After this resistive divider, there is a voltage of 0.375 to 0.875 V. Because The PGA400-Q1 accepts differential voltage, the other end is generated from the PGA400-Q1 DAC output2 (VOUT2). Now the differential input of the PGA will get a voltage in between –250 to 250 mV. This voltage is further amplified and given inside the delta-sigma ADC microcontroller to process it for linearity and temperature compensation. Finally, there is a ratio metric voltage of 0.5 to 4.5 V.

Figure 1. Signal Chain Voltage Levels

(1) The INA240 automotive version will be available in Q2 2017.
1.1 *Key System Specifications*

Table 1. Key System Specifications

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement parameter</td>
<td>Battery currents, motor currents, DC-DC converter currents</td>
</tr>
<tr>
<td>Sensor type</td>
<td>Shunt (resistive)</td>
</tr>
<tr>
<td>Shunt value</td>
<td>100 µΩ</td>
</tr>
<tr>
<td>Maximum current through the shunt</td>
<td>±500 A</td>
</tr>
<tr>
<td>Sensor power supply</td>
<td>12 V</td>
</tr>
<tr>
<td>Sensor current</td>
<td>14 mA</td>
</tr>
<tr>
<td>ADC (inside PGA400-Q1)</td>
<td>16-bit delta sigma</td>
</tr>
<tr>
<td>Overvoltage protection</td>
<td>Yes</td>
</tr>
<tr>
<td>Reverse polarity protection</td>
<td>Yes</td>
</tr>
<tr>
<td>Calibration</td>
<td>Linearity and compensation algorithm</td>
</tr>
<tr>
<td>Transient immunity</td>
<td>Designed to meet ISO7637-3 specifications</td>
</tr>
<tr>
<td>Output voltage</td>
<td>0.5 to 4.5 V</td>
</tr>
<tr>
<td>Output voltage protection</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature range</td>
<td>−40°C to 125°C</td>
</tr>
<tr>
<td>Harness faults protection</td>
<td>Yes</td>
</tr>
<tr>
<td>Digital Interface</td>
<td>SPI (for programming), UART (for evaluating and testing purpose)</td>
</tr>
<tr>
<td>Form factor</td>
<td>33-mm×36-mm rectangular PCB</td>
</tr>
</tbody>
</table>
2 System Overview

2.1 Block Diagram

The total system can be represented in four blocks:

- INA240: TI's current shunt monitor used to amplify the voltage across the shunt
- Attenuator: A resistive divider, used to match the signal levels between the INA240 and PGA400-Q1
- TPS709-Q1: Low Dropout Regulator (LDO), used to supply regulated voltage to the INA240 and PGA400-Q1
- PGA400-Q1: Signal conditioner, used mainly for linearity and temperature compensation purposes
2.2 Highlighted Products

2.2.1 INA240

The INA240 is a voltage-output, current-sense amplifier. The device is able to 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 implies good for low-side sensing as well. This device operates from a single 2.7-V to 5.5-V power supply, drawing a maximum of 2.4 mA of supply current. It can able to sense even smaller voltages as it has just 5uV typical offset error. Its excellent CMRR, compatibility with low sides and high sides, and bidirectional features make this a good device for this application. It is available in TSSOP package.

The main features of this device are as follows:

- Excellent CMRR:
  - 132-dB DC CMRR
  - 93-dB AC CMRR at 50 kHz
- Wide common-mode range: –4 to 80 V
- Accuracy:
  - Gain error: 0.20% (max)
  - Gain drift: 2.5 ppm/°C (max)
  - Offset voltage: ±25 μV (max)
  - Offset drift: 250 nV/°C (max)
- Quiescent current: 2.4 mA (max)
- Bidirectional sensing using reference pin configuration
- Available gains: 20, 50, 100, and 200
- AECQ100 qualified
- Device temperature grade 1: –40°C to 125 °C ambient operating temperature

2.2.2 PGA400-Q1

The PGA400-Q1 is mainly selected here for signal linearity and temperature compensation purpose. The device incorporates the analog front-end (AFE) that directly connects to the INA output and has voltage regulators and an oscillator. The device also includes a sigma-delta analog-to-digital converter (ADC), 8051 WARP core microprocessor, and OTP memory. Sensor compensation algorithms can be implemented in software. The PGA400-Q1 device also includes two digital-to-analog converter (DAC) outputs. The 16-bit delta sigma features most of the signal can be acquired with out any loss.

The main features of this device are as follows:

- 16-bit, 1-MHz delta-sigma ADC for signal channel
- In-chip temperature sensor enables temperature compensation easier
- Programmable gain
- Two 12-bit digital-to-analog outputs
- Microcontroller core: 8051 WARP core
- Peripheral features: UART, SPI, i²C, OWI
- AECQ100 qualified
- Device temperature grade 1: –40°C to 125°C ambient operating temperature
- Power supply: 4.5- to 5.5-V operational, –5.5- to 16-V absolute maximum
The TPS709-Q1 series of linear regulators are ultra-low quiescent current devices designed for power-sensitive applications. A precision band-gap and error amplifier provides 2% accuracy over temperature. A quiescent current of only 1 µA makes these devices ideal solutions for battery-powered, always-on systems that require very little idle-state power dissipation. These devices have thermal-shutdown, current-limit, and reverse-current protections for added safety.

These regulators can be put into shutdown mode by pulling the EN pin low. The shutdown current in this mode goes down to 150 nA, typical. The TPS709-Q1 series is available in WSON-6 and SOT-23-5 packages.

The main features of this device are as follows:
- Qualified for automotive applications
- Grade 1
- Input voltage range: 2.7 to 30 V
- Ultra-low $I_Q$: 1 µA
- Reverse current protection
- Low $I_{SHUTDOWN}$: 150 nA
- Supports 200-mA peak output
- 2% accuracy over temperature
- Available in fixed-output voltages: 1.2 to 6.5 V
- Thermal shutdown and overcurrent protection
2.3 System Design Theory

Current measurement information is required in many places in automotive for control, protection, monitoring, and power-management purposes. Examples include control of motor drives, converter control, overcurrent protection, state-of-the-charge estimation of batteries, and many more applications. Current measurement is intrusive as there is a need to insert some type of sensor. There are several other decisions to make related to current sensing, such as AC or DC measurements, complexity, linearity, sensitivity to noise, isolation requirements, accuracy, stability, robustness, bandwidth, transient response, cost, and power loss. Most current measurement approaches can be categorized as a resistive- or an electromagnetic-based technique. This TI Design uses resistive-based sensing. In resistive-based current-sensing techniques, the voltage drop across a sensing resistor is sensed to determine the current. Adding an external resistor to measure current is acceptable where power loss, low bandwidth, noise, and non-isolated measurement are acceptable. Several approaches use the bus bar or normal sensor resistors based on the current ranges. Selecting a sense resistor is the main critical factor in this TI Design. In sense resistor implementations, measurement accuracy is largely limited by:

- Temperature coefficient, TC, of the sense resistor
- Input offset error VOSI of the amplifier

A smaller value of the sense resistor usually results in degraded accuracy performance because the amplifier’s input offset error now constitutes a larger percentage of the applied signal at the amplifier input. The use of a larger value sense resistor, while beneficial for output accuracy, results in higher power dissipation. As a result, the sense resistor value for a design is usually chosen based on a design trade-off between sensing accuracy and power dissipation.

The next decision is on which topology to use: either low-side sensing or high-side sensing. For most applications, current measurements are made by sensing the voltage drop across a resistor. There are two locations in a circuit that resistors are commonly placed for current measurements. The first location is between the power supply and the load. This measurement method is referred to as high-side sensing. For the second location, a sense resistor is commonly placed is between the load and ground. This method of sensing the current is referred to as low-side current sensing. Both these methods to sense current in a load are shown in Figure 3. Both high- and low-side configurations have their own advantages and disadvantages based on customer requirements.

![Figure 3. Current Sensing Methods](image-url)
Current also needs to be sensed bidirectionally for some applications such as battery discharge and charging cycle monitoring purpose; this feature is needed to sense the current in both directions, battery discharges through the load, and charges from the outside power source. As shown in Figure 3, two shunts represents current and can be measured in either of the sides. Load sinks the current, which is called the discharging path; the battery is always losing its capacity here. This information is needed to know the exact state of charge of the battery. Otherwise, when the battery is charging by an external power source, this information is necessary to know the exact state of charge of the battery.

Along with these requirements, consider the following parameters when designing a current sensor solution:

- **Accuracy**: Decides the effectiveness of the system. It is the most important parameter because some control actions in the car need to be taken at exactly a point of time where some current value is reached.
- **Temperature effects**: Normally in automotive temperature, this varies from –40°C to 125°C. The design must withstands all these temperatures. The design needs to maintain the same accuracy throughout the entire temperature range.
- **Linearity**: The design should maintain linearity in this temperature range.
2.3.1 Design Procedure

As mentioned in Section 2.3, the main aim of this TI Design is to get the accuracy, linearity, and throughout the temperature range from –40°C to 125°C. The functional block diagram of the system is divided into three sections:

- Power supply
- Signal pickup using current shunt monitors
- Temperature and linearity compensation

2.3.1.1 Power Supply Section

Current sensors are powered up in different configurations based on their position. For example, when used in a 12-V battery system, sensors are powered up from the battery directly with the help of some linear regulators. When used in 48-V systems, they are powered up using DC-DC converters. When used in a BMS system, they are powered up from a control unit. Different topologies are also used based on the system in which the current sensor is used. In this reference design, the power supply is designed assuming this sensor is supplied from the 48-V to 12-V DC-DC followed by some linear regulators.

The transient voltage suppressor (TVS) is placed to suppress coupling transients according the ISO7637-3 standard. Based on the power-up topology, different kinds of protections are needed for transients. For example, if the system is connected directly from the battery, then the TVS needs supplying load dump protection. In this TI Design, it is assumed that the sensor is supplied from the DC-DC converter. An external TVS diode of 400 W and 33 V of clamping voltage diode is selected to suppress coupling transients.

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The circuit was made according to ISO 7637-3 standards and as per this standard, there are two main types of coupling effects on supply lines: capacitive or inductive. The strength of pulses according to level IV would be in magnitudes of –60 V and 40 V and with varying times. These coupling effects are from the supply lines because the coupling transients occur as a result of wiring harness faults. The diode breakdown voltages must be chosen such that transients are clamped at voltages that will protect the reverse polarity protection diode, TPS709-Q1, and the rest of the system. In this TI Design, there is a need to protect a continuous 20-V signal (harness faults), so the breakdown voltage of the TVS should be more than 20 V. A typical 23.4-V breakdown voltage diode is selected to serve this purpose. A TVS diode with a breakdown voltage of 24 V and a clamping voltage of 33 V is selected. The reverse clamping device will clamp all negative voltages greater than the battery voltage so it does not short out during a reverse-battery condition.
The other parameter to choose for the TVS diodes is the peak power rating. This is important because it is proportional to the package size of the diodes. Measure the amount of peak power that the diode can see to size the package properly. The important features are its clamping voltage, the voltage of the pulse it is clamping, and the source impedance of the pulse. The rise time and duration of the pulse also play a role, although not an immediate one.

The following is an example of calculating for Pulse B from ISO 7637-3, which ends up being the worst case (test level IV):

- \( V_{\text{PULSE}} = 40 \text{ V} \)
- \( R_{\text{SOURCE}} = 50 \Omega \)
- \( V_{\text{CLAMP}} = 32.4 \text{ V} \) (for 10/1000 µs)

The worst case assumption is that the load draws very little current, so the majority will go through the TVS diodes. If \( V_{\text{PULSE}} = 32.4 \text{ V} \) and the pulse generator generates a 40-V pulse, this implies that there is a 7-V drop across \( R_1 \) (the source impedance of the pulse as defined in ISO 7637-3), 7.6 V / 50 Ω = 0.152 A, coming out of the pulse generator. Most of this passes through the TVS diode, and so one can estimate the peak power seen by the device as \( P = I \times V = 32.4 \text{ V} \times 0.152 \text{ A} = 4.9248 \text{ W} \). Based on the specifications listed, a 400-W, 32.4-V clamping voltage TVS diode is selected.

![Figure 6. Power Supply Section Schematic Diagram](image-url)

Two capacitors in 'L' configuration are used. These act as power supply capacitors. The 'L' configuration protects the sensor from vibration tests (typical in automotive).

A normal diode serves the purpose of reverse polarity. Here, a normal diode is enough because the sensor consumes only 14 mA and the voltage drop of the diode forward for the 14-mA forward current is 0.4V, implies 5.6mW of power dissipation.

The INA240 and PGA400-Q1 accepts 5 V. The PGA400-Q1 has already linear regulators built in. However, the INA240 needs some kind of regulation; for exactly this purpose, the TPS709-Q1 is selected. This LDO has a very good accuracy range (2%) and has a much lower less drop of 150 mA, which offers fixed range selection options. The output of the TPS709-Q1 is a 5-V regulated output. In case of harness faults, the input might get 20 V continuous, and this LDO can able to withstand 20 V continuous.

As shown in Figure 6, this power supply section is transient, protected against overvoltage and reverse polarity. Using simple buffer capacitors, the respective stages can be driven.
2.3.1.2 Signal Chain Section

The main goal of signal chain electronics is to sense ±500 A of current with the good accuracy over the entire grade 1 temperature range. For this purpose, a shunt approach has been selected. Basically in shunt approaches, a current is made to pass through the lower value of a resistor (or a shunt), and the drop across this resistor is measured with the help of current shunt monitors. As shown in Figure 7, ±500 A of current is made to pass through the 100-µΩ shunt implies that across the shunt, –50 to 50 mV is dropped. This is very minute amount of voltage, and this needs to be sensed and amplified with a very precise device. TI’s current shunt monitors are some of the best class devices, which suit this application perfectly. The INA240 senses the voltage in between –50 to 50 mV differentially, and with a gain factor of 20 V/V, it gives an output in between 1.5 to 3.5 V. The INA240 has a reference voltage of 2.5 V, and the DC offset of the device stays at 2.5 V. This 2.5 V is generated from the PGA400-Q1 DAC output.

This current sensor is assumed to be for a 48-V system, so when connecting this in the high side, it sees a voltage of 48 V, which implies the common-mode voltage of the device should be more than this 48 V. The INA240 has a maximum common-mode voltage of 80 V, so it is a safe case here. As shown in Figure 7, two TVS diodes are connected for the two ends of the shunt. Breakdown voltage of the TVS is selected as 58.1 V because it should not clamp before that as it is a 48-V system. Each TVS diode is capable of handling 600 W, which implies together they can withstand 1200 W of power. The TVS diode power rating has to be changed depending on the protection level needed.

Figure 7. Current Shunt Monitor Connection With Shunt Resistor

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The output of the INA240 is given to the PGA400-Q1 to compensate for temperature and linearity. Also, the PGA400-Q1 inputs are differential, but the INA240 output is single ended; the other end is generated from the PGA400-Q1 DAC as shown in Figure 8. Now the differential voltage is −1.5 to 1.5 V, and the PGA400-Q1 inputs cannot accept this voltage. There needs to be a signal matching mechanism, which translates the levels to match the PGA400-Q1 input requirements. For this purpose, an attenuator with 1/4 attenuation is created. The attenuator is just a resistive divider made with 0.1% tolerance resistors. After the attenuator section, the output differential voltage is from −250 to 250 mV and it matches with the PGA400-Q1 perfectly.

The PGA400-Q1 has built-in gain stages that offer a further gain of 6 V/V before giving the signal to the delta-sigma ADC. The 16-bit ADC senses the signal and converts it into digital values. These values are given to the built-in 8051 controller. This microcontroller is programmed in such a way that it takes the values from the onboard temperature sensor and provides temperature compensation for the entire range using a linearity and temperature compensation algorithm. With the help of the built-in DAC, the ratio of the metric analog output is given as an output, which varies in between 0.5 to 4.5 V.

The output section of the whole system is also protected against harness faults (see Figure 9). The output protection is achieved by combining a Zener diode and resettable fuse. This circuit consists of a series element, a resettable fuse, and a parallel element Zener diode. The series element limits the current, and the parallel element clamps the voltage level. The resettable fuse disconnects or breaks when there is a large current passing through the fuse.

Figure 8. PGA400-Q1 Connection With Attenuator and INA240
When an input voltage exceeds the breakdown voltage parameter of the Zener diode, there is a sudden surge in current through the Zener diode and in the resettable fuse. The temperature increases in the fuse, which causes the fuse to break the circuit. The resistance of the fuse will increase many folds, which is equivalent to the circuit being open. When the overvoltage condition is removed, the current stops flowing through the fuse and the temperature of the fuse reduces, thus closing the circuit again after some time.

Figure 9. Output Protection

2.3.2 Harness Fault Conditions and Solutions

Table 2 describes the possible combinations of harness faults for the sensor mechanism. The circuit is designed to meet all these harness faults. Each case describes the way these fault conditions are handled.

Table 2. Harness Fault Conditions

<table>
<thead>
<tr>
<th>FAULT NO</th>
<th>DEVICE VDD</th>
<th>DEVICE GND</th>
<th>DEVICE VOUT</th>
<th>REMARK</th>
<th>DEVICE STATUS AFTER REMOVAL OF FAILURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 V</td>
<td>0 V</td>
<td>Pull up to VDD</td>
<td>Normal connection with VOUT to pulled to VDD</td>
<td>Safe</td>
</tr>
<tr>
<td>2</td>
<td>5 V</td>
<td>0 V</td>
<td>Pull down to GND</td>
<td>Normal connection with VOUT to pulled to GND</td>
<td>Safe</td>
</tr>
<tr>
<td>3</td>
<td>20 V</td>
<td>0 V</td>
<td>GND to VDD</td>
<td>Overvoltage</td>
<td>Safe</td>
</tr>
<tr>
<td>4</td>
<td>Open</td>
<td>0 V</td>
<td>Pull up to VDD</td>
<td>Open VDD with VOUT pulled to VDD</td>
<td>Safe</td>
</tr>
<tr>
<td>5</td>
<td>Open</td>
<td>0 V</td>
<td>Pull down to GND</td>
<td>Open VDD with VOUT pulled to GND</td>
<td>Safe</td>
</tr>
<tr>
<td>6</td>
<td>5 V</td>
<td>Open</td>
<td>Pull up to VDD</td>
<td>Open GND with VOUT pulled to VDD</td>
<td>Safe</td>
</tr>
<tr>
<td>7</td>
<td>5 V</td>
<td>Open</td>
<td>Pull down to GND</td>
<td>Open GND with VOUT pulled to GND</td>
<td>Safe</td>
</tr>
<tr>
<td>8</td>
<td>0 V</td>
<td>20 V</td>
<td>Pull up to VDD</td>
<td>Reverse voltage with VOUT pulled to VDD</td>
<td>Safe</td>
</tr>
<tr>
<td>9</td>
<td>0 V</td>
<td>20 V</td>
<td>Pull down to GND</td>
<td>Reverse voltage with VOUT pulled to GND</td>
<td>Safe</td>
</tr>
<tr>
<td>10</td>
<td>0 V</td>
<td>0 V</td>
<td>Pull up to VDD</td>
<td>VDD shorted to GND with VOUT pulled to VDD</td>
<td>Safe</td>
</tr>
<tr>
<td>11</td>
<td>0 V</td>
<td>0 V</td>
<td>Pull down to GND</td>
<td>VDD shorted to GND with VOUT pulled to GND</td>
<td>Safe</td>
</tr>
<tr>
<td>12</td>
<td>20 V</td>
<td>20 V</td>
<td>Pull up to VDD</td>
<td>GND shorted to VDD with VOUT pulled to VDD</td>
<td>Safe</td>
</tr>
<tr>
<td>13</td>
<td>20 V</td>
<td>20 V</td>
<td>Pull down to GND</td>
<td>GND shorted to VDD with VOUT pulled to GND</td>
<td>Safe</td>
</tr>
<tr>
<td>14</td>
<td>20 V</td>
<td>0 V</td>
<td>20 V</td>
<td>VOUT Shorted to VDD</td>
<td>Safe</td>
</tr>
<tr>
<td>15</td>
<td>20 V</td>
<td>0 V</td>
<td>Pull down to GND</td>
<td>VOUT Shorted to GND</td>
<td>Safe</td>
</tr>
</tbody>
</table>
2.3.2.1 Case 1: $V_{DD} = 5 \, V$, $GND = 0 \, V$, $VOUT = 5 \, V (VDD)$

Apply a voltage (5 V) to output pin through a 1-kΩ pullup resistor. Internal current limit protection is available when the output is at 5 V (30-mA short to battery). No external protection circuitry is required. This is a safe case and the signal follows the normal path.

![Diagram](image1.png)

Figure 10. Output Connected to 5 V

2.3.2.2 Case 2: $V_{DD} = 5 \, V$, $GND = 0 \, V$, $VOUT = 0 \, V (GND)$

Set the output to ground and the power supply at 5 V. A dead short to ground can allow as much as 30 mA of current to flow. This is a safe case.

![Diagram](image2.png)

Figure 11. Short to Ground Connection
2.3.2.3 Case 3: \( \text{VDD} = 20 \text{ V}, \text{GND} = 0 \text{ V}, \text{VOUT} = 5 \text{ V} \) (VDD)

The power supply section opens (overvoltage condition). When the output is at 5 V with VDD open, all circuits inside the PGA400-Q1 try to power up, but nothing happens to the device as it cannot pass much current inside (see Section 2.3.2.14).

Figure 12. Overvoltage Condition at Supply and Output

2.3.2.4 Case 4: \( \text{VDD} = \text{OPEN}, \text{GND} = 0 \text{ V}, \text{VOUT} = 5 \text{ V} \) (VDD)

As described in Section 2.3.2.3, the power supply section opens. When the output is at 5 V with VDD open, all circuits inside the PGA400-Q1 try to power up, but nothing happens to the device as it will not pass much current inside. This is a safe case.

2.3.2.5 CASE 5: \( \text{VDD} = \text{OPEN}, \text{GND} = 0 \text{ V}, \text{VOUT} = 0 \text{ V} \) (GND)

In this case, there is no possibility of excess current to flow because no potential exists. This is a safe case.

2.3.2.6 CASE 6: \( \text{VDD} = 5 \text{ V}, \text{GND} = \text{OPEN}, \text{VOUT} = 5 \text{ V} \) (VDD)

The two ends of the internal pullup diode are at the same voltage. There is no path for the excess current to flow as the diode is not conducting. This is a safe case.

2.3.2.7 CASE 7: \( \text{VDD} = 5 \text{ V}, \text{GND} = \text{OPEN}, \text{VOUT} = 0 \text{ V} \) (GND)

All the internal circuits of the PGA400-Q1 get power and try to discharge through the VOUT pulldown diode.
2.3.2.8 CASE 8: VDD = 0 V, GND = 20 V, VOUT = 5 V (VDD)

In the power supply section, reverse voltage protection is achieved using a normal diode. As shown in Figure 13, when the reverse voltage is applied across the terminals, the diode blocks it from entering in wrong configuration. This implies that the other part of the circuit is floating. VDD of the PGA400-Q1 is open because of the reverse polarity protection implemented. The device is safe.

![Diagram](image-url)

**Figure 13. Reverse Polarity Protection and Output Overvoltage Protection**

Now the condition evolves into an open VDD with a GND of 20 V, and output is at 5 V. As described in Figure 13, there exists a high-current path in between the 5- and 20-V supply. The output fuse opens as high current flows, implying the output is floating. As a result, the output and VDD are open. The device is safe.

2.3.2.9 CASE 9: VDD = 0 V, GND = 20 V, VOUT = 0 V (GND)

Reverse voltage protection is applied and the circuit behaves according to Section 2.3.2.8 (VDD opens). Output is grounded with VDD open and ground at 20 V. There is no path for the current to flow through the PGA400-Q1 because supply is open and no closed loop exists. The only possibility for the current to flow is through a Zener diode to fuse to the output. The Zener diode forward current is 200 mA; when the current is more than 200 mA, the fuse opens and the circuits survive.

2.3.2.10 CASE 10: VDD = 0 V, GND = 0 V, VOUT = 5 V (VDD)

There is no effect on the circuit (see Section 2.3.2.4). This is a safe case.

2.3.2.11 CASE 11: VDD = 0 V, GND = 0 V, VOUT = 0 V (GND)

There is no effect on the circuit as everything is grounded, and no potential exists in the circuit (see Section 2.3.2.5). This is a safe case.
2.3.2.12 **CASE 12: VDD = 20 V, GND = 20 V, VOUT = 20 V**

The initial PMOS does not have enough voltage (threshold voltage) to turn ON; both positive and negative supplies are in 20 V. VCC opens. On the output section, applying 20 V with respect to 20 V (GND) means nothing is applied (GND) across the output. The output shorted to 0 V, same as Section 2.3.2.5. This is a safe case.

2.3.2.13 **CASE 13: VDD = 20 V, GND = 20 V, VOUT = 0 V (GND)**

VDD is open and the output is grounded (Section 2.3.2.5). This is a safe case.

2.3.2.14 **Case 14: VDD = 20 V, GND = 0 V, VOUT = 20 V**

Once the voltage at the output pin is greater than the supply voltage (5 V) by about 0.5 V, the internal top diode (pullup diode) starts to conduct and it cannot tolerate high voltages, resulting in a high voltage across the output pin, which might damage the chip. Implement output protection in this case. Also, according to absolute maximum ratings of the PGA400-Q1, it can only survive until it reaches 16 V. Applying 20 V might damage the chip. Overvoltage protection is needed in this case for 20 V. The LDO accepts 20 V, and the output 5 V. The 20-V output is shown in Figure 14.

2.3.2.15 **Case 14: VDD = 20 V, GND = 0 V, VOUT = 0V (GND)**

VDD is 5 V and output is grounded (see Section 2.3.2.5). This is a safe case. The output is short to ground and the power supply is at 20 V (overvoltage), implying VDD opens. With the VDD open and output grounded, there is no potential existing in the network. The device is safe.
3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

±500 A of current is made to pass through the shunt, and the resulting voltage is given to the signal conditioning unit. In this TI Design, instead of directly passing ±500 A through the shunt, the voltage across the shunt is emulated using a precision source meter. First calibrate the device, then perform basic functional tests proceeded by temperature variation tests. The main testing objective is to prove that the current sensor maintains an accuracy of <0.2% FSR over the entire temperature range of –40°C to 125°C.

For the initial board setup, the following equipment is required:

- TIDA-03040 PCB with the PGA400-Q1 preprogrammed on it
- PGA400-Q1 EVM with TI-GER USB board
- PC (PGA 301 GUI installed)
- 12-V battery or power supply
- HP 3458A 8½ digit multimeter (preferably)
- Keysight 34410A 6½ digit multimeter (preferably)
- Keysight source meter B2912A (preferably)

To calibrate the PGA400-Q1 for a particular sense element, connect the hardware as shown in Figure 15.

3.1.1.1 Hardware Setup for Calibration

To connect the circuit as described in Figure 15:

1. Connect the 12-V power supply or battery to a connector.
2. Connect the output wire to the HP 3458A 8½ digit multimeter.
3. Connect the Keysight 6½ digit multimeter across the shunt terminals.
4. Connect the 12-V power supply to the PGA400-Q1 EVM (100-mA current limitation).
5. Connect the output terminal of the TIDA-03040 to the GPIO: VOUT1 pin of PGA400-Q1 EVM (to establish OWI), as shown in Figure 15.
6. Connect the EVM and TIDA-03040 grounds.
7. Connect the PGA400-Q1 EVM to the PC through TI-GER USB board.
8. Connect the jumpers on the PGA400-Q1 EVM as by default (it is recommended to verify once from the device datasheet).
Figure 15. TIDA-03040 Connection to PGA400-Q1 EVM for Calibration
Figure 16 shows the testing connection diagram. Equivalent source meter voltages are applied across the inputs of the INA240. The three wires from the connector featured in Figure 15 are the 12-V supply (orange), ground (black), and VOUT (purple). VOUT is connected to the respective control unit in the car. Normally, an output signal is taken using a pullup resistor.
3.1.1.2  Calibration Procedure

To calibrate the PGA400-Q1 for a particular sense element, the user needs to calibrate the PGA400-Q1 for the entire temperature range. The device can be calibrated using the OWI pin of the PGA400-Q1 or using SPI communication. The VOUT pin on the PGA400-Q1 is responsible for OWI communication. OWI driver circuitry and PC interface (TI-GER USB board) circuitry is available on the PGA400-Q1 EVM, so the PGA400-Q1 EVM needs to be interfaced with the TIDA-03040 in order to calibrate. Connect the PGA400-Q1 EVM to the TIDA-03040 board as shown in Figure 15.

The following steps describe the calibration procedure in detail.

3.1.1.2.1  Step 1: Set up Hardware and Software

Connect the hardware as described in Section 3.1.1.1 and in Figure 15.

Before starting the calibration procedure, import the appropriate software on the PGA400-Q1 device. Find the PGA400-Q1_CurrentSensorProgram hex file from the TIDA-03040 tool folder and import as described:

1. Open the PGA400-Q1 GUI (comes with PGA400-Q1 EVM).
2. Click on the TEST tab and click on `IFSEL/uC_RST`. After this, the button goes to green color and under TEST → 0E MICRO CTL it should display "03". This clarifies that hardware is properly connected and can start importing the program.
3. Click on the OTP tab.
4. Click `LOAD .HEX File into GUI` and select the hex file from the computer. It takes about 1 minute to import, and at the end it displays the message "program verification successful".

3.1.1.2.2  Step 2: Check Software

Verify all the listed required files are available before starting the calibration procedure:

- PGA400-Q1 GUI
- PGA400-Q1 coefficient calculations spreadsheet
- PGA400-Q1 signal chain spreadsheet

3.1.1.2.3  Step 3: Activate OWI

1. Power up the EVM power supply and the TIDA-03040 power supply.
2. Start the PGA400-Q1 GUI.
3. Click on `OWI` in the right half of the GUI. Click on `Activate OWI with Over-Voltage Drive → Activate TIGER UART`.
4. Click on the TEST tab in the left half of the GUI and click on `IFSEL/uc_RST` to reset the microcontroller. "03" should appear under the register `OE MICRO CTL`. This verifies that the hardware is connected properly and the sensor is ready for calibration.
3.1.1.2.4 Step 4: Set the Gain and Offset

1. To calibrate, apply the source meter voltages across the input of the INA240. This implies the PGA400-Q1 sees voltages in between –250 to 250 mV.

2. Configure Gain 1 and Gain 2 using the PGA400-Q1 signal chain spreadsheet in such a way to get the ADC input in between –1.65 to 1.65 V.

3. Enter the Gain 1 and Gain 2 values in the EEPROM → BANK_5 → SEN1GAIN section. In this case, Gain 1 = 3.00 and Gain 2 = 1.00 are selected (which gives ADC input in between –1.65 to 1.65 V). Enter “00HEX)” in the SEN1GAIN section in EEPROM BANK5 [see Section 7.3.4: Sensor 1 Gain Register (SEN1GAIN) of the PGA400-Q1-EP datasheet for details].

4. Go to EEPROM BANK_5 → SEN1OFF1 = 00, SEN1OFF2 = A0.

5. Click WRITE ALL.

6. Click AUTO PROGRAM EEPROM.

7. Click Reload Cache to verify whether it is written in EEPROM registers or not. The GUI should look like Figure 18.

Figure 18. EEPROM BANK_5 Registers
3.1.1.2.5 Step 5: Calibrate ADC

To calibrate the three signal points and three temperature points (3P-3T; –20°C, 50°C, 120°C):

1. Place the TIDA-03040 in the temperature chamber and set the temperature to –20°C.
2. Unreset the microcontroller by clicking on the IFSEL/uC_RST tab.
3. Place the sensor at its minimum current (~250 mV in this case).
4. Start OWI and reset the micro by clicking on the IFSEL/uC_RST tab.
5. Go to the ADC Conversion Result tab in the right half of the GUI.
6. Click ADC Continuous.
7. In 1 to 2 minutes, it generates a PADC.csv file in the folder where the GUI is located. Take the average of 500 generated values and enter the value in the PGA400-Q1 coefficient calculations spreadsheet under current ADC → Pmin → Tmin.
8. Repeat Steps 2 through 6 for the sensor maximum and mid voltages (250 mV and 0 mV in this case) and enter the ADC Continuous averaged value under Pmax and Pmid (PGA400-Q1 coefficient calculations spreadsheet under current ADC → Pmin → Tmin and → Pmid → Tmax), respectively.
9. Click ADC Continuous.
10. In 1 to 2 minutes, it generates a ADC.csv file in the folder where the GUI is located. Take the average of 500 generated values and enter the value in the PGA400-Q1 coefficient calculations spreadsheet under the following locations:
   - TEMPERATURE ADC → Pmin → Tmin
   - TEMPERATURE ADC → Pmid → Tmin
   - TEMPERATURE ADC → Pmax → Tmin
11. Set the chamber temperature to 45°C.
12. Repeat Steps 2 through 6.
13. In 1 to 2 minutes, it generates a ADC.csv file in the folder where the GUI is located. Take the average of 500 generated values and enter the value in the PGA400-Q1 coefficient calculations spreadsheet under current ADC → Pmin → Tmid.
14. Repeat Steps 2 through 6 for the sensor maximum and mid voltages (250 mV and 0 mV in this case) and enter the ADC Continuous averaged value under Pmax and Pmid (PGA400-Q1 coefficient calculations spreadsheet under current ADC → Pmin → Tmid and → Pmid → Tmid), respectively.
15. Click ADC Continuous.
16. In 1 to 2 minutes, it generates a ADC.csv file in the folder where the GUI is located. Take the average of 500 generated values and enter the value in the PGA400-Q1 coefficient calculations spreadsheet under the following locations:
   - TEMPERATURE ADC → Pmin → Tmid
   - TEMPERATURE ADC → Pmid → Tmid
   - TEMPERATURE ADC → Pmax → Tmid
17. Set the temperature to 120°C.
18. Repeat Steps 2 through 6.
19. In 1 to 2 minutes, it generates a ADC.csv file in the folder where the GUI is located. Take the average of 500 generated values and enter the value in the PGA400-Q1 coefficient calculations spreadsheet under current ADC → Pmin → Tmax.
20. Repeat Steps 2 through 6 for the sensor maximum and mid voltages (250 mV and 0 mV in this case) and enter ADC Continuous averaged value under Pmax and Pmid (PGA400-Q1 coefficient calculations spreadsheet under current ADC → Pmin → Tmax and → Pmid → Tmax), respectively.
21. Click ADC Continuous.
22. In 1 to 2 minutes, it generates a ADC.csv file in the folder where the GUI is located. Take the average of 500 generated values and enter the value in the PGA400-Q1 coefficient calculations spreadsheet under the following locations:

- TEMPERATURE ADC → Pmin → Tmax
- TEMPERATURE ADC → Pmid → Tmax
- TEMPERATURE ADC → Pmax → Tmax

3.1.1.2.6 Step 6: Calibrate DAC

For 3P-3T (–20°C, 45°C, 120°C):

1. Place the TIDA-03040 in the temperature chamber and set the temperature to –20°C.
2. Start OWI and reset the microcontroller.
3. Go to EEPROM BANK4 → DAC CAL ENABLE = 01.
4. Go to EEPROM BANK4 → DACCALMSB = 01, DACCALLSB = 9C.
5. Unreset the micro by placing "00" in 0E MICRO CTL (under the TEST tab).
6. Measure the output voltage of DAC using the multimeter (HP 3458 8½ digit multimeter) and enter the measured value in the PGA400-Q1 coefficient calculations spreadsheet (3P-3T DAC) under Pmin → Tmin Measured VOUT.
7. Start OWI and reset the microcontroller.
8. Go to EEPROM BANK4 → DACCALMSB = 07, DACCALLSB = FD.
9. Unreset the micro by placing "00" in 0E MICRO CTL (under the TEST tab).
10. Measure the output voltage of DAC using the multimeter (HP 3458 8½ digit multimeter) and enter the measured value in the PGA400-Q1 coefficient calculations spreadsheet (3P-3T DAC) under Pmid → Tmin Measured VOUT.
11. Start OWI and reset MICRO.
12. Go to EEPROM BANK4 → DACCALMSB = 0E, DACCALLSB = 60.
13. Unreset the microcontroller by placing "00" in 0E MICRO CTL (under the TEST tab).
14. Measure the output voltage of DAC using the multimeter (HP 3458 8½ digit multimeter) and enter the measured value in the PGA400-Q1 coefficient calculations spreadsheet (3P-3T DAC) under Pmax → Tmin Measured VOUT.
15. Measure the VDD voltage from the test point 1 available on the TIDA-03040 board and enter in the spreadsheet under Tmin VDD.
16. Place the TIDA-03040 in the temperature chamber and set the temperature to 45°C.
17. Repeat Steps 2 through 14 but enter the respective values in:
   - Pmin → Tmid Measured VOUT
   - Pmid → Tmid Measured VOUT
   - Pmax → Tmid Measured VOUT
18. Measure the VDD voltage from the test point 1 available on the TIDA-03040 board and enter in the spreadsheet under Tmid VDD.
19. Place the TIDA-03040 in the temperature chamber and set the temperature to 125°C.
20. Repeat Steps 2 through 14 but enter the respective values in:
   - Pmin → Tmax Measured VOUT
   - Pmid → Tmax Measured VOUT
   - Pmax → Tmax Measured VOUT
21. Measure the VDD voltage from the test point 1 available on the TIDA-03040 board and enter in the spreadsheet under Tmax VDD. Finally, the spreadsheet should look like Figure 19.

3.1.1.2.7 Step 7: Calculate Coefficients

For 3P-3T (−20°C, 45°C, 120°C):
1. In the coefficient calculations spreadsheet under 3P-3T ADC, note the N0, G0, H0, N1, G1, H1, N2, G2, and H2 values that are generated based on ADC and DAC measurements as described in Section 3.1.1.2.4 to Section 3.1.1.2.6.
2. Go to the PGA400-Q1 GUI.
3. Start OWI and reset the microcontroller.
4. Click EEPROM → BANK_1 and enter the N0, G0, H0, N1, G1, H1, G2, and H2 values as per the EEPROM memory MAP spreadsheet.
5. Click WRITE ALL.
6. Click AUTO PROGRAM EEPROM.
7. Click Reload Cache to verify whether it is written in EEPROM registers or not.
8. Click EEPROM → BANK_2 and enter the N2 value as per the EEPROM memory MAP spreadsheet.
9. Click WRITE ALL.
10. Click AUTO PROGRAM EEPROM.
11. Click Reload Cache to verify if it is written in EEPROM registers or not. The coefficients in the spreadsheet should look like Figure 21:

![Figure 20. Coefficients for 3P-3T Configuration](image-url)
The GUI should look like Figure 21:

Figure 21. EEPROM BANK_1 Register Values
3.1.1.2.8   Step 8: PGA400-Q1-EEPROM BANK_2 Registers

1. Click EEPROM → BANK_2.
2. Enter the values as shown in Figure 22:

3. Click WRITE ALL.
4. Click AUTO PROGRAM EEPROM.
5. Click Reload Cache to verify whether it is written in EEPROM registers or not.
Step 9: PGA400-Q1-EEPROM BANK_3 Registers

1. Click EEPROM → BANK_3.
2. Enter the values as shown in Figure 23:

![Figure 23. EEPROM BANK_3 Register Values](image)

3. Click WRITE ALL.
4. Click AUTO PROGRAM EEPROM.
5. Click Reload Cache to verify whether it is written in EEPROM registers or not.
3.1.1.2.10  Step 10: PGA400-Q1-EEPROM BANK_4 Registers

1. Click **EEPROM → BANK_4**.
2. Enter the values as shown in Figure 24:

![Figure 24. EEPROM BANK_4 Register Values](image)

3. Click **WRITE ALL**.
4. Click **AUTO PROGRAM EEPROM**.
5. Click **Reload Cache** to verify whether it is written in EEPROM registers or not.

3.1.1.2.11  Step 11: Unreset Microcontroller

Unreset the microcontroller by placing "00" in 0E MICRO CTL (under the TEST tab).

3.1.2  Software

Linearization and compensation algorithms have been developed in software. The software files named `PGA400-Q1_CurrentSensorProgram` are available in the TIDA-03040 tools folder.
### 3.2 Testing and Results

The testing procedures outlined in this design guide are designed to ensure proper functionality and to analyze the effects of harness faults on the current sensor system.

#### 3.2.1 Basic Functionality

Apply current through the shunt with a 500-A power supply or precision source meter, as shown in Figure 25.

![Figure 25. Testing Connection Diagram](image)

**Figure 25. Testing Connection Diagram**

Set the chamber temperature to 25°C and apply voltages in even intervals from –50 to 50 mV (see the exact applied voltage in the 6½ digit multimeter). Note the output voltage corresponding to the particular input. Table 3 and Figure 26 show the applied input voltages and corresponding output voltages.

The expected voltage can be calculated using Equation 1 and Equation 2. The sensor input voltage range is –50 to 50 mV, and the output span is 0.5 to 4.5 V.

The expected voltage for minimum sensor voltage must be 0.5 V. The output of the PGA400-Q1 is ratio-metric, so the output depends on the supply voltage variations. The following equations describe the ratio-metric calculations.

\[
\text{Output expected (V)} = \frac{\text{Supply voltage (V)} \times 0.5}{5} = \frac{4.9722 \times 0.5}{5} = 0.49722 \text{ V}
\]

(1)

Full-scale (FS) accuracy can be calculated using Equation 2.

\[
\text{FS accuracy} = \text{Output expected (V)} - \text{Output measured (V)} \times \frac{100}{\text{Output span}}
\]

(2)

\[
\text{FS accuracy} = 0.49722 - 0.492 \times \frac{100}{4} = 0.1305\%
\]
### Table 3. Sensor Readings and FS Accuracy Calculations

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<td>2.21512088</td>
<td>2.2117</td>
</tr>
<tr>
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<td>−8.0120</td>
<td>−80.120</td>
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<td>2.17516096</td>
<td>2.1721</td>
</tr>
<tr>
<td>34</td>
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<td>−90.120</td>
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<td>2.1318</td>
</tr>
<tr>
<td>35</td>
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<td>−100.120</td>
<td>4.99</td>
<td>2.09532096</td>
<td>2.0923</td>
</tr>
<tr>
<td>36</td>
<td>−15.0120</td>
<td>−150.120</td>
<td>4.99</td>
<td>1.89572096</td>
<td>1.8925</td>
</tr>
<tr>
<td>37</td>
<td>−20.0120</td>
<td>−200.120</td>
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<td>1.6922</td>
</tr>
<tr>
<td>38</td>
<td>−25.0130</td>
<td>−250.130</td>
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<td>1.4926</td>
</tr>
<tr>
<td>39</td>
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<td>1.2934</td>
</tr>
<tr>
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<td>−350.130</td>
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<td>1.0946</td>
</tr>
<tr>
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<td>−40.0145</td>
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<td>0.8952</td>
</tr>
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<tr>
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<td>−500.145</td>
<td>4.99</td>
<td>0.49842116</td>
<td>0.4969</td>
</tr>
</tbody>
</table>

(1) Maximum deviation observed
When the curve is drawn in between the input current and accuracy as shown in Figure 26, FS accuracy is less than 0.1%. Normally, current sensors show their worst behavior when the current is in the lower ranges. However, as shown in Table 3 when the current is in these lower ranges, for example 1 A, the error here is 0.0823% FSR.
3.2.2 Temperature Dependence

In general, current-based measurements vary with respect to temperature, which results in poor accuracy. The PGA400-Q1 temperature and compensation algorithm provides good accuracy over the grade 1 temperature range. Second order linearity compensation algorithms have imported inside the PGA400-Q1 to compensate the temperature changes and to give more accurate result.

3.2.2.1 Temperature versus Output Current Variations

The following tables show the variation of output voltage with respect to temperature. Set up the experiment as shown in Figure 25 and change the temperatures in increments of 20°C.

The PGA400-Q1 has a built-in temperature compensation algorithm. Using the internal temperature sensor and compensation algorithm, the output voltage changes are minimized with respect to temperature changes. Table 4 shows the effect on output voltage accuracy over the grade 1 temperature range (–40°C to 125°C) when the current values is at its minimum. For calculations of expected output and accuracy, see Equation 1 and Equation 2 from Section 3.2.1.

Table 4. Output Voltage Change With Respect to Temperature at Minimum Input Current

<table>
<thead>
<tr>
<th>TEMPERATURE (°C)</th>
<th>INPUT (P_MIN) (mV)</th>
<th>EQUIVALENT CURRENT (A)</th>
<th>SUPPLY (V)</th>
<th>EXPECTED OUTPUT (V)</th>
<th>MEASURED OUTPUT (V)</th>
<th>FS ACCURACY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>–40</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9950</td>
<td>0.49950</td>
<td>0.4989</td>
<td>0.01500</td>
</tr>
<tr>
<td>–20</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9940</td>
<td>0.49940</td>
<td>0.4980</td>
<td>0.03500</td>
</tr>
<tr>
<td>0</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9930</td>
<td>0.49930</td>
<td>0.4969</td>
<td>0.06000</td>
</tr>
<tr>
<td>25</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9900</td>
<td>0.49900</td>
<td>0.4970</td>
<td>0.05000</td>
</tr>
<tr>
<td>50</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9860</td>
<td>0.49860</td>
<td>0.4972</td>
<td>0.03500</td>
</tr>
<tr>
<td>80</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9800</td>
<td>0.49800</td>
<td>0.4988</td>
<td>–0.02000</td>
</tr>
<tr>
<td>100</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9765</td>
<td>0.49765</td>
<td>0.5011</td>
<td>–0.08625</td>
</tr>
<tr>
<td>120</td>
<td>–50.001</td>
<td>–500.01</td>
<td>4.9980</td>
<td>0.49980</td>
<td>0.5070</td>
<td>–0.18000</td>
</tr>
<tr>
<td>125</td>
<td>–50.001</td>
<td>–500.01</td>
<td>5.0030</td>
<td>0.50030</td>
<td>0.5080</td>
<td>–0.19250(1)</td>
</tr>
</tbody>
</table>

(1) Maximum deviation observed among all the other variations

From Table 4, the variation of output voltage over the defined temperature range is very low (accuracy of –0.1925%) when the input is at its minimum value.

Table 5 shows the effect on output voltage accuracy over the grade 1 temperature range (–40°C to 125°C). When the input is locked at a medium value and changes from –40°C to 125°C, the output voltage variation can be seen in the accuracy column in Table 5.

Table 5. Output Voltage Change With Respect to Temperature at Medium Input Current

<table>
<thead>
<tr>
<th>TEMPERATURE (°C)</th>
<th>INPUT (P_MID) (mV)</th>
<th>EQUIVALENT CURRENT (A)</th>
<th>SUPPLY (V)</th>
<th>EXPECTED OUTPUT (V)</th>
<th>MEASURED OUTPUT (V)</th>
<th>FS ACCURACY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>–40</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9950</td>
<td>2.49750</td>
<td>2.4947</td>
<td>0.07000</td>
</tr>
<tr>
<td>–20</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9940</td>
<td>2.49700</td>
<td>2.4943</td>
<td>0.06750</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9930</td>
<td>2.49650</td>
<td>2.4933</td>
<td>0.08000(1)</td>
</tr>
<tr>
<td>25</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9900</td>
<td>2.49500</td>
<td>2.4922</td>
<td>0.07000</td>
</tr>
<tr>
<td>50</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9860</td>
<td>2.49300</td>
<td>2.4907</td>
<td>0.05750</td>
</tr>
<tr>
<td>80</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9800</td>
<td>2.49000</td>
<td>2.4872</td>
<td>0.07000</td>
</tr>
<tr>
<td>100</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9765</td>
<td>2.48825</td>
<td>2.4851</td>
<td>0.07875</td>
</tr>
<tr>
<td>120</td>
<td>0.01</td>
<td>0.1</td>
<td>4.9980</td>
<td>2.49900</td>
<td>2.4960</td>
<td>0.07500</td>
</tr>
<tr>
<td>125</td>
<td>0.01</td>
<td>0.1</td>
<td>5.0030</td>
<td>2.50150</td>
<td>2.5007</td>
<td>0.02000</td>
</tr>
</tbody>
</table>

(1) Maximum deviation observed among all other variations
From Table 4, the variation of output voltage over the defined temperature range is very low (accuracy of 0.08%) when the input is at its medium value.

**Table 6** shows the effect on output voltage accuracy over the grade 1 temperature range (−40°C to 125°C). When the input is locked at the maximum value and changes the temperatures from −40°C to 125°C, the output voltage variation can be seen in **Table 6**.

**Table 6. Output Voltage Change With Respect to Temperature at Maximum Input Current**

<table>
<thead>
<tr>
<th>TEMPERATURE (°C)</th>
<th>INPUT (P_max) (mV)</th>
<th>EQUIVALENT CURRENT (A)</th>
<th>SUPPLY (V)</th>
<th>EXPECTED OUTPUT (V)</th>
<th>MEASURED OUTPUT (V)</th>
<th>FS ACCURACY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−40</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9950</td>
<td>4.4950</td>
<td>4.4941</td>
<td>0.0350</td>
</tr>
<tr>
<td>−20</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9940</td>
<td>4.4940</td>
<td>4.4929</td>
<td>0.0425</td>
</tr>
<tr>
<td>0</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9930</td>
<td>4.4930</td>
<td>4.4911</td>
<td>0.0650</td>
</tr>
<tr>
<td>25</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9900</td>
<td>4.4900</td>
<td>4.4886</td>
<td>0.0600</td>
</tr>
<tr>
<td>50</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9860</td>
<td>4.4860</td>
<td>4.4850</td>
<td>0.0600</td>
</tr>
<tr>
<td>80</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9800</td>
<td>4.4800</td>
<td>4.4793</td>
<td>0.0675</td>
</tr>
<tr>
<td>100</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9765</td>
<td>4.4765</td>
<td>4.4760</td>
<td>0.0712 (1)</td>
</tr>
<tr>
<td>120</td>
<td>49.99</td>
<td>499.9</td>
<td>4.9980</td>
<td>4.4980</td>
<td>4.4973</td>
<td>0.0225</td>
</tr>
<tr>
<td>125</td>
<td>49.99</td>
<td>499.9</td>
<td>5.0030</td>
<td>4.50270</td>
<td>4.5023</td>
<td>0.0100</td>
</tr>
</tbody>
</table>

(1) Maximum deviation observed among all other variations

From **Table 6**, the variation of output voltage over the defined temperature range is low (accuracy of −0.071%) when the input is at its maximum value.
4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-03040.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-03040.

4.3 PCB Layout Recommendations

Layout is one of the critical factors when concerning about current sensor design. Follow these guidelines when designing a current sensor solution:

- Shunt resistor must maintain the symmetry when connecting to the current shunt monitor (INA240).
- Configure the layout so that there is a Kelvin connection between the INA240 and shunt resistor.
- Use the shortest possible distance when connecting the shunt and the INA240.
- Place the shunt exactly on top of shunt instead of placing it on the edges. The problem with placing the INA240 on the edges is that magnetic field lines will cross it, making it ineffective. Instead, placing it on top gives the device a parallel cross section.
- Place the two TVS diodes on the edges by maintaining the symmetry (consider more grounding for the TVS diode discharge path).
- Construct two pads with a maximum area to give more power dissipation area.
- Place buffer capacitors as close as possible with the ICs.
- Place ground planes on top and bottom.

Figure 27. TIDA-03040 Top Layer Layout Guidelines

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-03040.
4.4 **Altium Project**
To download the Altium project files, see the design files at TIDA-03040.

4.5 **Gerber Files**
To download the Gerber files, see the design files at TIDA-03040.

4.6 **Assembly Drawings**
To download the assembly drawings, see the design files at TIDA-03040.

5 **Software Files**
To download the software files, see the design files at TIDA-03040.

6 **Related Documentation**

6.1 **Trademarks**
All trademarks are the property of their respective owners.

7 **About the Author**
SANDEEP TALLADA is a systems engineer at Texas Instruments. As a member of the Automotive Systems Engineering team, Sandeep focuses on powertrain end-equipment and creating subsystem reference designs. He brings to this role experience in sensor systems technology. Sandeep earned his master of science in sensor systems technology from the University of Applied Sciences Karlsruhe, Germany.
## Revision A History

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

<table>
<thead>
<tr>
<th>Changes from Original (February 2017) to A Revision</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Changed voltage for sensor power supply from 5 V to 12 V</td>
<td>3</td>
</tr>
<tr>
<td>• Deleted the 4 next to Output span in Equation 2</td>
<td>30</td>
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<tr>
<td>• Added &quot;FS&quot; to the y-axis title in Figure 26</td>
<td>32</td>
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