*Kareem Moulana*

# *TI Designs – Precision: Verified Design*
# *30A Range Bidirectional Current Shunt Monitor*

## TI Designs – Precision

TI Designs – Precision are analog solutions created by TI's analog experts. Verified Designs offer the theory, component selection, simulation, complete PCB schematic & layout, bill of materials, and measured performance of useful circuits. Circuit modifications that help to meet alternate design goals are also discussed.

## Circuit Description

This verified design can accurately measure current across a range of 30 A on a bus that carries up to 36-V common mode voltage over a range of -40℃ to +85℃. This design can measure current from 0 A to 30 A with a grounded reference or -30 A to 0 A with a 16-V reference. The design sums the output of two INA250A2 devices and generates a ground-referenced output voltage. The INA250 is a voltage-output, current-sensing amplifier family that integrates an internal shunt resistor to enable high-accuracy current measurements.

## Design Resources

| | |
|---|---|
| Design Archive | All Design files |
| TINA-TI™ | SPICE Simulator |
| INA250 | Product Folder |

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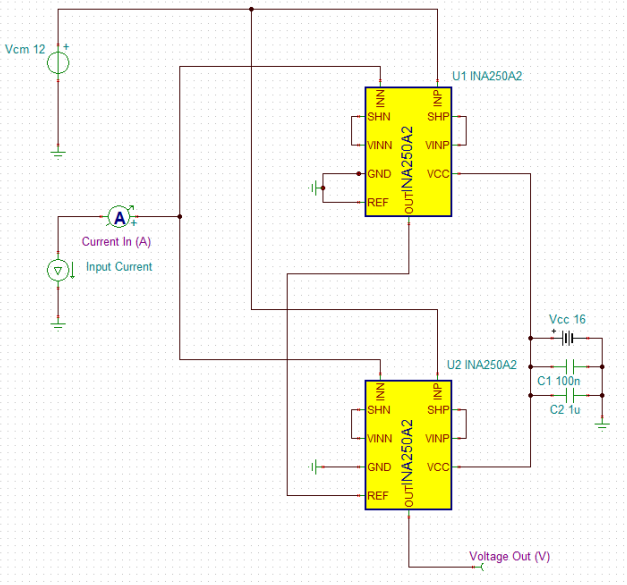


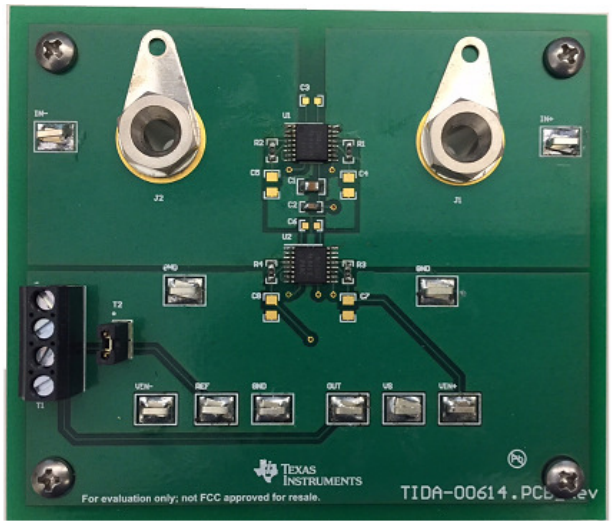


**CAUTION: This equipment operates at high currents which can result in hazardous electrical shock. Please make sure you understand and follow all necessary safety precautions prior to purchasing and operating.**

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## 1 Design operation

The design requirements are as follows:

- Supply Voltage: 2.7 V to 36 V
- Ability to measure current from 0 A to 30 A or -30 A to 0 A
- Gain: 500 mV/A
- Common-Mode Voltage: 0 V to 36 V

The design goals and performance are summarized in Table 1. Figure 1 depicts the measured total error of the design. Data was taken with a cooling fan both off and on to demonstrate the thermal stability of the design.

**Table 1. Comparison of Design Goals and Measured Performance**

| | Goal | Measured |
|---|---|---|
| **Relative Error ($I_{load}$= 30 A)** | 0.682% | 0.593% |
| **Relative Error ($I_{load}$= 15 A)** | 1.123% | 0.572% |
| **Relative Error ($I_{load}$= -15 A)** | 1.123% | 0.067% |
| **Relative Error ($I_{load}$= -30 A)** | 0.682% | 0.400% |

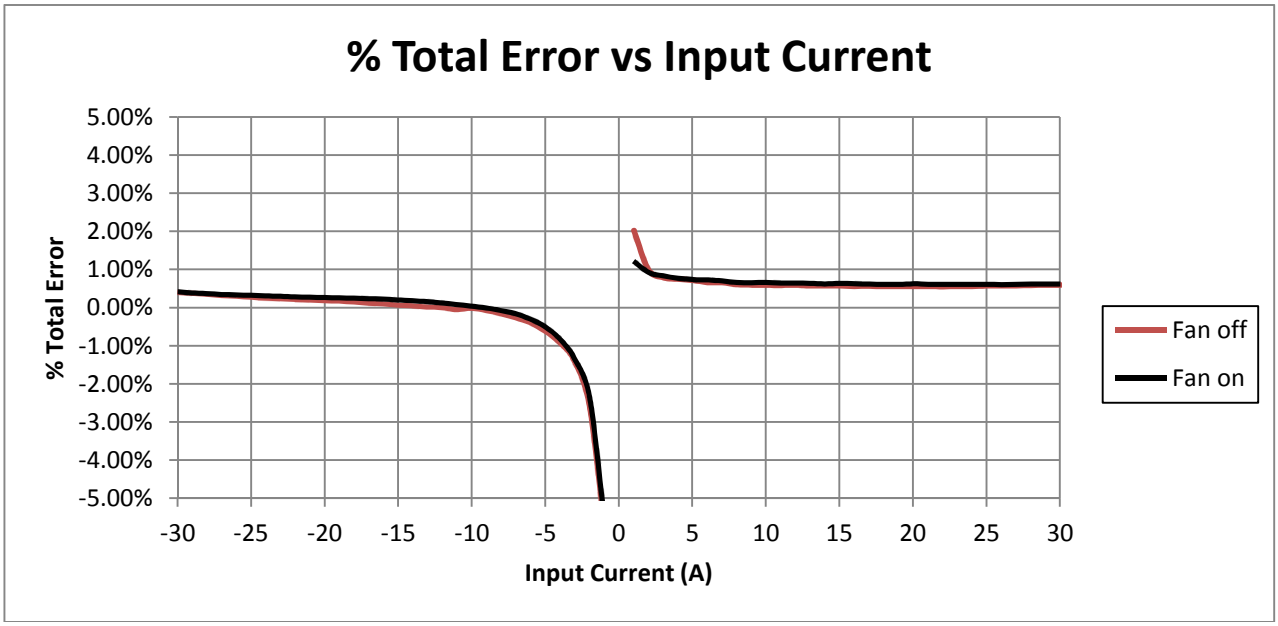


**Figure 1: Measured Total Error**

## 2 Theory of Operation

The INA250A2 can only measure continuous bus currents of up to 15 A. To be able to measure currents in excess of 15 A, two INA250A2 devices are used in parallel. The design uses two Texas Instruments INA250A2 current shunt monitors in a current summing configuration to measure load current across a 30-A range. The current through the bus is divided so that approximately half passes through each device; at 30 A of load current, each device will measure 15 A.

The basic idea of the design is shown in Figure 2. Since the INA250A2 has a gain of 500 mV/A, the first device (which is ground referenced) will output 7.5 V for the 15 A it senses. This output is then tied into the reference input of the second INA250A2. The second device then sums its own output to the reference input. In the case of 30 A of load current, the system will output 15 V from the output of the second device.

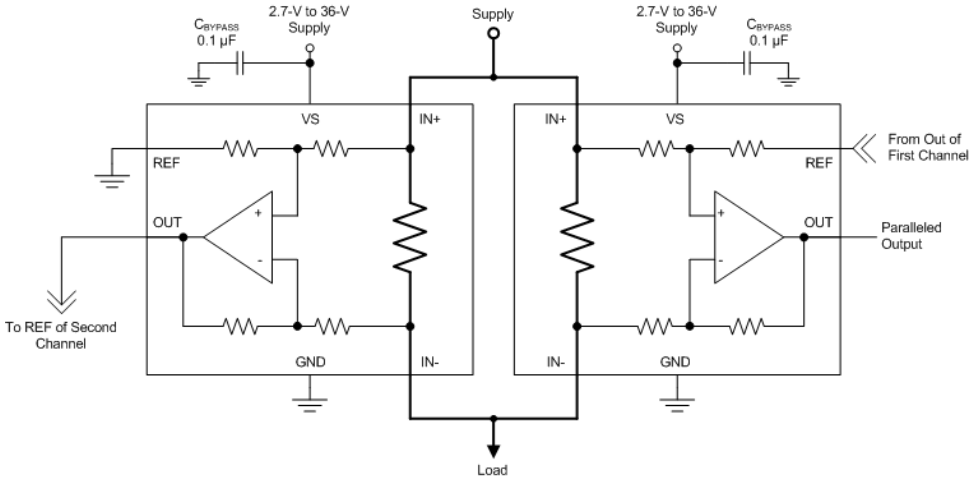


**Figure 2: TI Design Basic Block Diagram**

### *2.1 Current Summing Limitations*

This approach does have a limitation—the reference input to an INA250 cannot exceed 18 V. This means that sensing across a full 60-A range of -30 A to +30 A is not possible with this design, which utilizes an INA250A2 (with a gain of 500 mV/A) without changing the reference input voltage. Instead this design is aimed at sensing a 30-A range (for example 0 A to +30 A or -30 A to 0 A).

If, for example, $V_{REF}$ for the first device was set at 15 V with the objective of sensing a -30 A to +30 A current range, the output of the design would theoretically swing from 0 V to 30 V. However, in this configuration the output of the first device would exceed 18 V, which is the absolute maximum value for the $V_{REF}$. Since the output of the first device is fed into the $V_{REF}$ of the second device, this configuration is outside the region of safe operation for this design.

### *2.2 INA250 Filtering*

The TI Design board has optional input filters to remove high-frequency noise from the inputs VIN+ and VIN-. The default values for R1, R2, R3, and R4 are 0-Ω resistors. Figure 3 shows the recommended values for the filter. Figure 4 shows the location of the filter on the board. The board is populated with four 0-Ω resistors (R1, R2, R3, and R4); however the filter capacitors (C3, C4, C5, C6, C7, and C8) are optional and were not installed at the time of testing. If a filter is needed, use the lowest possible series resistance (typically 10-Ω or less) and ceramic capacitors. Recommended values for these capacitors are 0.1-µF to 1.0-µF. In many cases a filter is not needed.

> **NOTE**: Make sure the 0-Ω resistors are populated on the board, otherwise the input to the VIN+ and VIN- pins will be open and the device will not operate.

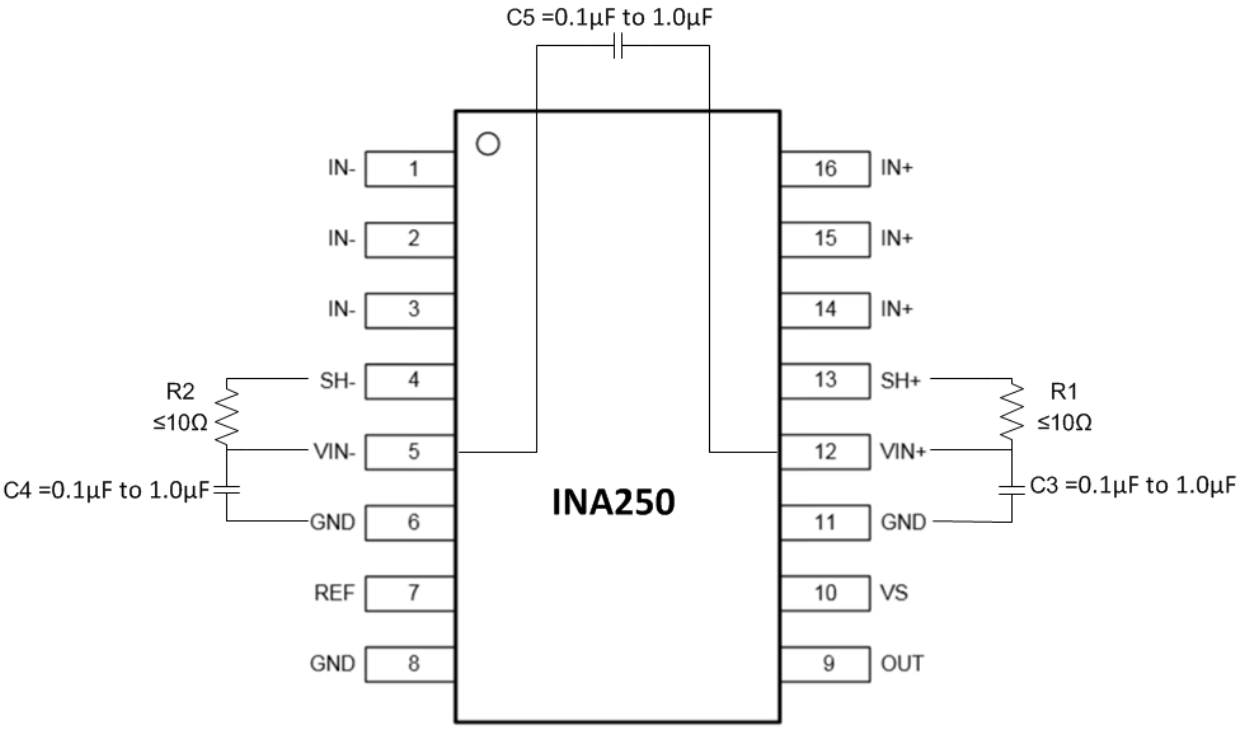


**Figure 3: Input Filter**

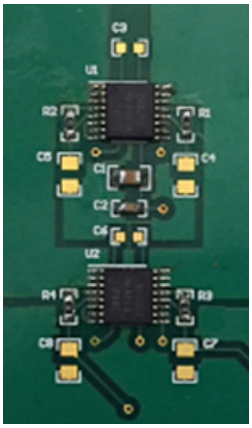

**Figure 4: Location of Input Filters in the TI Design board**

## 3 Component Selection

### *3.1 INA250A2*

For this design, a current shunt monitor with a wide input current sensing range, analog output, high accuracy, and the benefit of an internal shunt are needed. The current shunt monitor chosen for this application is the INA250A2. This device not only has the resolution and accuracy needed to achieve the design goals, but has the current paralleling and summing ability required to sense 30 A of continuous current.

The INA250 is a family of voltage-output, current sensing amplifiers that integrates an internal shunt resistor to enable high-accuracy current measurements at common-mode voltages that can vary from 0 V to 36 V, independent of supply voltage. Figure 5 shows the basic block diagram of the INA250. For more information about INA250 features please refer to the INA250 datasheet.

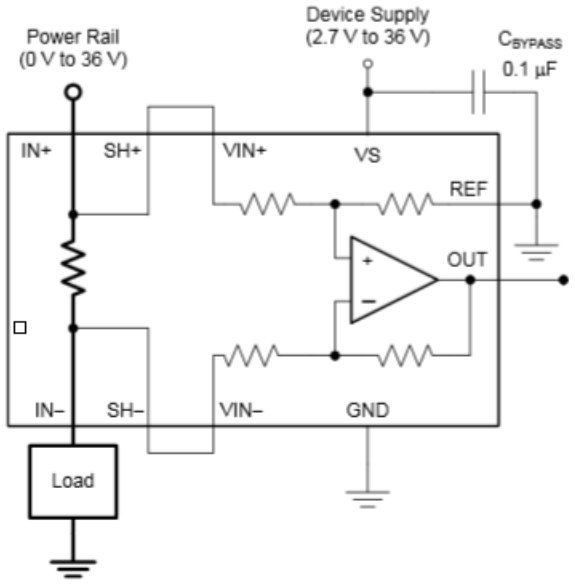


**Figure 5: INA250 Basic Block Diagram**

## 4 Simulation

### *4.1 Steady State*

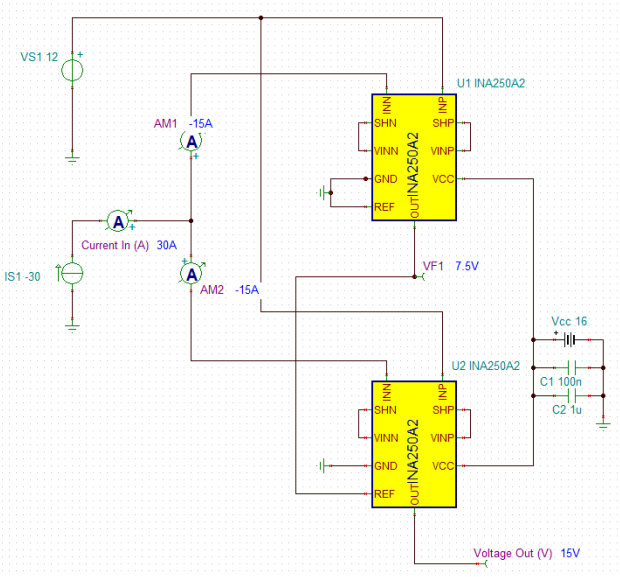


**Figure 6: DC Circuit Simulation**

In Figure 6 a steady state simulation of the circuit with 30 A of input current is illustrated. Note that the input into the reference pin of the second device (U2) is safely below the 18 V limit. The first device (U1) measures 15 A and outputs 7.5 V since its reference is tied to ground. This 7.5 V acts as a reference for the second device (U2).

The second device (U2) also measures 15 A, and adds an additional 7.5 V to its reference, resulting in an overall output of 15 V with respect to ground.

### 4.2 Transient

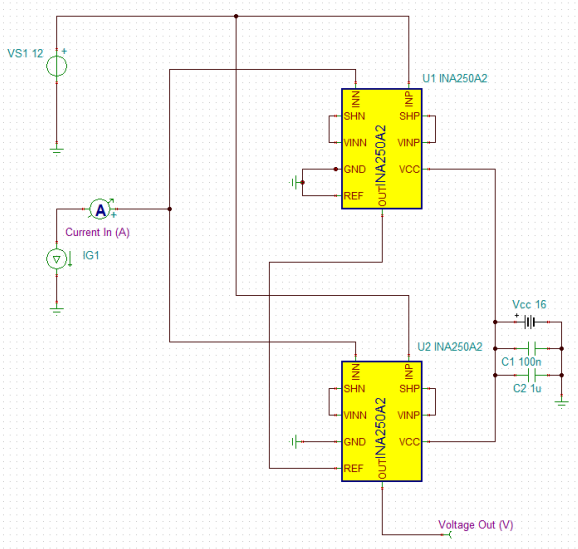


**Figure 7: AC Circuit Simulation**

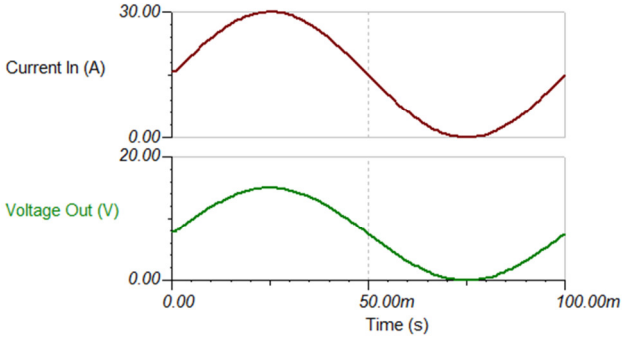


**Figure 8: AC Circuit Results**

In Figure 8, the results of an AC input signal are observed. The simulation output waveform shows the design operating properly by outputting 500 mV/A in response to the input current. The input is a sine wave with the following characteristics:

- DC level: 15 A
- Amplitude: 15 A
- Frequency: 10 Hz

## 5 PCB Design

The PCB schematic and bill of materials are found in the Appendix.

### 5.1 PCB Layout

The PCB used in this design is 3.2” by 2.75”. There are large planes to accommodate the large amounts of current through the design. All of the circuitry could be contained in approximately 0.5” by 1”, however large copper traces are necessary to safely conduct high current—without good thermal layout the design would be limited to 20 A continuous current. As seen in Figure 9, the IN- and IN+ traces carry current to the devices.

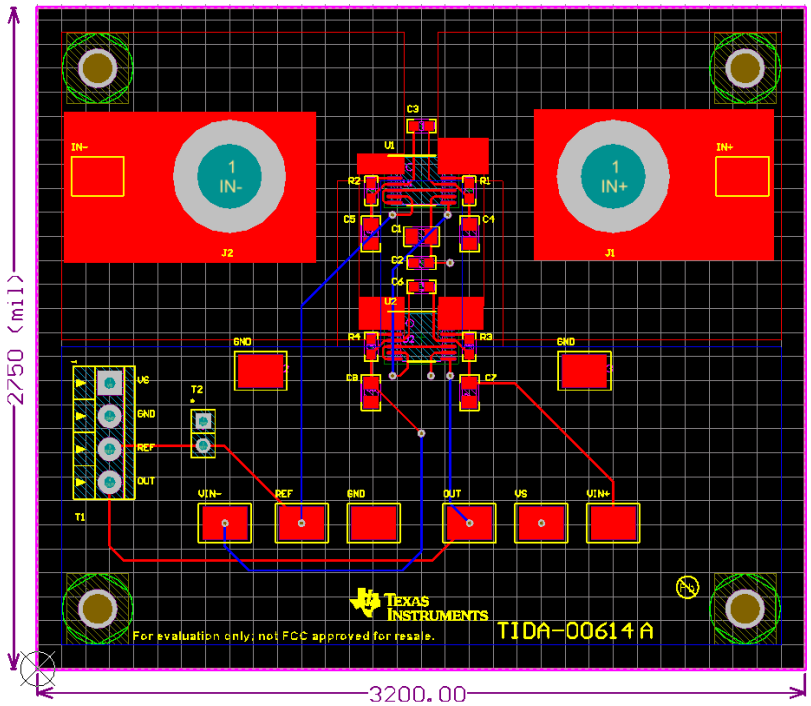


**Figure 9: PCB Layout**

It is important to place the bypass caps C1 and C2 close to the devices. This makes the design more stable by reducing noise thereby increasing accuracy.

A horizontal line that divides the PCB roughly in half is seen in Figure 9. This line effectively separates the high current half of the board from the low current half of the board below it. The terminal block T1 has all the connections needed for the operation of the INA250A2 devices on the board (VS, REF, and GND) as well as a terminal for the voltage output (OUT). All of these signals are also available as test points on the low current side of the board.

Jumper T2 is available to connect REF to GND. When the jumper is installed, REF is tied to GND.

# 6 Verification & Measured Performance

## *6.1 Measuring Design Performance*

### *6.1.1 Measured Total Error*

Data was collected by sweeping the load current from -30 A to 0 A with a reference voltage of 16 V, and then from 0 A to 30 A with a reference voltage of 0 V. The load current was verified with a TGHGCR0010FE (1 mΩ, 1%, 100W) resistor. Table 2 shows the data collected with no external cooling fan. Table 3 shows data collected with an external cooling fan. Figure 1 demonstrates the thermal stability of the design as well as its total error by plotting total error data with and without external cooling.

The measured gain of the board has been calculated with Equation (1), which is then used to calculate the %Total Error of the design in Equation (2).

$$Measured\ Gain = \frac{(V_{out} - V_{ref})}{I_{load}} \quad (1)$$

$$\%Total\ Error = \frac{Measured\ Gain - 0.5}{0.5} \times 100 \quad (2)$$

**Table 2. Data collected with fan off**

| Current In (A) | Voltage Out (V) | Measured Gain (V/A) | % Error | Current In (A) | Voltage Out (V) | Measured Gain (V/A) | % Error |
|---|---|---|---|---|---|---|---|
| -30.006 | 1.057 | 0.4980 | 0.400% | 1.031 | 0.5051 | 0.4899 | 2.017% |
| -29.017 | 1.546 | 0.4981 | 0.376% | 2.023 | 1.002 | 0.4951 | 0.989% |
| -28.016 | 2.041 | 0.4983 | 0.350% | 3.05 | 1.513 | 0.4961 | 0.787% |
| -27.022 | 2.532 | 0.4984 | 0.318% | 4.01 | 1.990 | 0.4963 | 0.748% |
| -26.019 | 3.029 | 0.4985 | 0.296% | 5.03 | 2.497 | 0.4964 | 0.716% |
| -25.014 | 3.527 | 0.4986 | 0.272% | 6.038 | 2.999 | 0.4967 | 0.662% |
| -24.03 | 4.015 | 0.4988 | 0.250% | 7.014 | 3.484 | 0.4967 | 0.656% |
| -23.028 | 4.513 | 0.4988 | 0.234% | 8.031 | 3.991 | 0.4969 | 0.610% |
| -22.024 | 5.012 | 0.4989 | 0.218% | 9.078 | 4.512 | 0.4970 | 0.595% |
| -21.022 | 5.51 | 0.4990 | 0.200% | 10.021 | 4.981 | 0.4971 | 0.589% |
| -20.04 | 5.998 | 0.4991 | 0.180% | 11.079 | 5.507 | 0.4971 | 0.587% |
| -19.02 | 6.506 | 0.4992 | 0.168% | 12.001 | 5.965 | 0.4970 | 0.592% |
| -18.008 | 7.009 | 0.4993 | 0.144% | 13.035 | 6.480 | 0.4971 | 0.575% |
| -17.016 | 7.502 | 0.4994 | 0.118% | 14.059 | 6.989 | 0.4971 | 0.576% |
| -16.014 | 8.001 | 0.4995 | 0.100% | 15.042 | 7.478 | 0.4971 | 0.572% |
| -15.032 | 8.489 | 0.4997 | 0.067% | 16.02 | 7.965 | 0.4972 | 0.562% |
| -14.056 | 8.975 | 0.4998 | 0.043% | 17.018 | 8.461 | 0.4972 | 0.564% |
| -13.062 | 9.47 | 0.4999 | 0.015% | 18.012 | 8.956 | 0.4972 | 0.555% |
| -12.048 | 9.976 | 0.5000 | 0.000% | 19.056 | 9.475 | 0.4972 | 0.556% |
| -11.042 | 10.476 | 0.5003 | -0.054% | 20.074 | 9.981 | 0.4972 | 0.558% |
| -10.006 | 10.996 | 0.5001 | -0.020% | 21.044 | 10.463 | 0.4972 | 0.561% |
| -9.021 | 11.486 | 0.5004 | -0.078% | 22.076 | 10.977 | 0.4972 | 0.553% |
| -8.005 | 11.991 | 0.5008 | -0.162% | 23.047 | 11.459 | 0.4972 | 0.560% |
| -7.019 | 12.481 | 0.5014 | -0.271% | 24.025 | 11.945 | 0.4972 | 0.562% |
| -6.032 | 12.972 | 0.5020 | -0.398% | 25.007 | 12.432 | 0.4971 | 0.572% |
| -5.023 | 13.473 | 0.5031 | -0.617% | 26.069 | 12.960 | 0.4971 | 0.572% |
| -4.061 | 13.951 | 0.5046 | -0.911% | 27.024 | 13.434 | 0.4971 | 0.577% |
| -3.08 | 14.439 | 0.5068 | -1.364% | 28.032 | 13.934 | 0.4971 | 0.585% |
| -2.033 | 14.958 | 0.5125 | -2.509% | 29.038 | 14.433 | 0.4970 | 0.592% |
| -1.003 | 15.47 | 0.5284 | -5.683% | 30.042 | 14.932 | 0.4970 | 0.593% |

**Table 3. Data collected with fan off**

| Current In (A) | Voltage Out (V) | Measured Gain (V/A) | % Error | | Current In (A) | Voltage Out (V) | Measured Gain (V/A) | % Error |
|---|---|---|---|---|---|---|---|---|
| -29.992 | 1.066 | 0.4979 | 0.413% | | 1.002 | 0.4949 | 0.4939 | 1.218% |
| -29.056 | 1.528 | 0.4981 | 0.385% | | 2.044 | 1.013 | 0.4954 | 0.920% |
| -28.025 | 2.039 | 0.4982 | 0.368% | | 3.003 | 1.489 | 0.4958 | 0.833% |
| -27.009 | 2.542 | 0.4983 | 0.344% | | 4.023 | 1.996 | 0.4961 | 0.771% |
| -26.016 | 3.035 | 0.4983 | 0.331% | | 5.045 | 2.504 | 0.4963 | 0.733% |
| -25.025 | 3.528 | 0.4984 | 0.324% | | 6.094 | 3.025 | 0.4964 | 0.722% |
| -24.04 | 4.017 | 0.4985 | 0.308% | | 7.021 | 3.486 | 0.4965 | 0.698% |
| -23.006 | 4.531 | 0.4985 | 0.296% | | 8.017 | 3.982 | 0.4967 | 0.661% |
| -22.034 | 5.014 | 0.4986 | 0.281% | | 9.033 | 4.487 | 0.4967 | 0.653% |
| -21.021 | 5.518 | 0.4986 | 0.271% | | 10.02 | 4.977 | 0.4967 | 0.659% |
| -20.005 | 6.024 | 0.4987 | 0.265% | | 11.005 | 5.467 | 0.4968 | 0.645% |
| -19.008 | 6.520 | 0.4987 | 0.253% | | 12.021 | 5.972 | 0.4968 | 0.641% |
| -18.016 | 7.014 | 0.4988 | 0.244% | | 13.015 | 6.466 | 0.4968 | 0.638% |
| -17.025 | 7.507 | 0.4989 | 0.229% | | 14.009 | 6.961 | 0.4969 | 0.621% |
| -16.044 | 7.996 | 0.4989 | 0.224% | | 15.048 | 7.476 | 0.4968 | 0.638% |
| -15.082 | 8.474 | 0.4990 | 0.199% | | 16.04 | 7.970 | 0.4969 | 0.623% |
| -14.035 | 8.995 | 0.4991 | 0.178% | | 17.055 | 8.475 | 0.4969 | 0.616% |
| -13.008 | 9.506 | 0.4992 | 0.154% | | 18.038 | 8.964 | 0.4970 | 0.610% |
| -12.087 | 9.964 | 0.4994 | 0.124% | | 19.062 | 9.473 | 0.4970 | 0.609% |
| -11.081 | 10.464 | 0.4996 | 0.081% | | 20.055 | 9.965 | 0.4969 | 0.623% |
| -10.068 | 10.968 | 0.4998 | 0.040% | | 21.053 | 10.462 | 0.4969 | 0.613% |
| -9.007 | 11.496 | 0.5001 | -0.011% | | 22.035 | 10.950 | 0.4969 | 0.613% |
| -8.052 | 11.971 | 0.5004 | -0.075% | | 23.088 | 11.474 | 0.4970 | 0.606% |
| -7.067 | 12.461 | 0.5008 | -0.156% | | 24.07 | 11.962 | 0.4970 | 0.607% |
| -6.048 | 12.967 | 0.5015 | -0.298% | | 25.03 | 12.439 | 0.4970 | 0.607% |
| -5.019 | 13.478 | 0.5025 | -0.498% | | 26.031 | 12.937 | 0.4970 | 0.603% |
| -4.009 | 13.979 | 0.5041 | -0.823% | | 27.032 | 13.434 | 0.4970 | 0.607% |
| -3.03 | 14.465 | 0.5066 | -1.320% | | 28.05 | 13.939 | 0.4969 | 0.613% |
| -2.008 | 14.973 | 0.5115 | -2.291% | | 29.081 | 14.451 | 0.4969 | 0.616% |
| -1.027 | 15.459 | 0.5268 | -5.355% | | 30.026 | 14.920 | 0.4969 | 0.619% |

### 6.1.2 Thermal Stability

Data was also collected on the thermal stability of this design. The steady state temperature was measured at different levels of input current. The design was found to operate safely with or without external cooling, though the temperature of the board can self-heat up to 70℃ from room temperature without an external fan when operated at 30 A continuously.

Figures 10 and 11 show the steady state temperatures at varying input currents with and without an external fan.

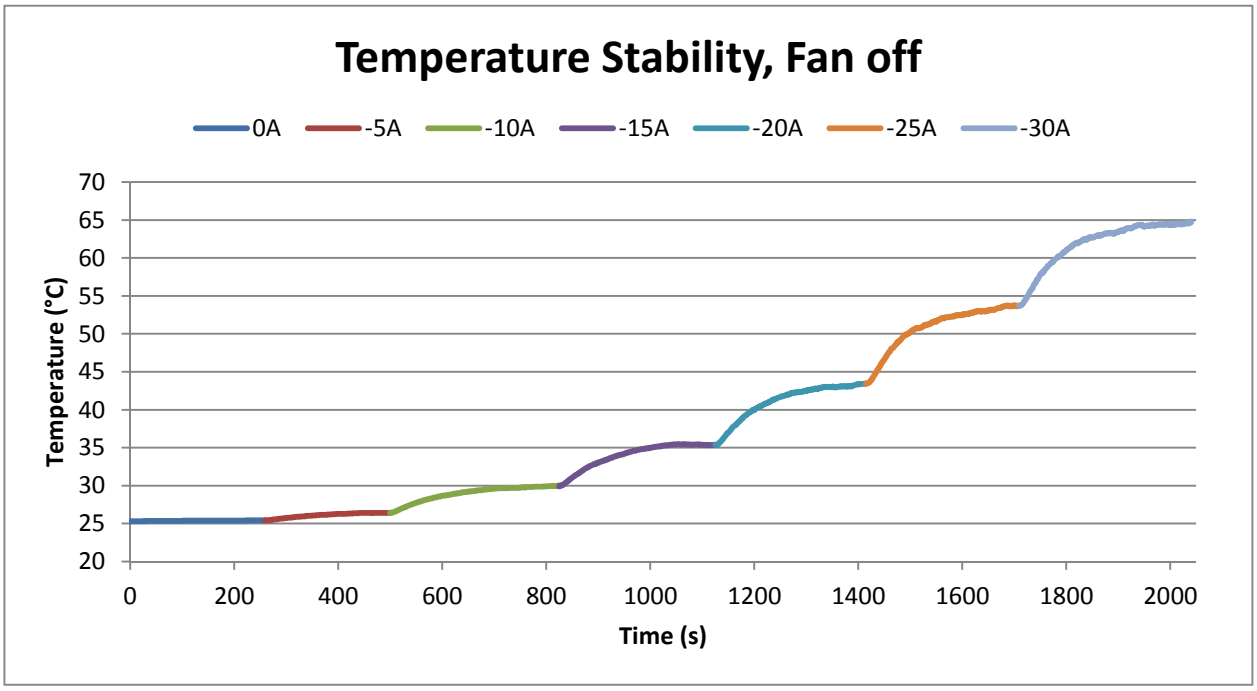


**Figure 10: Steady State Temperature, fan off**

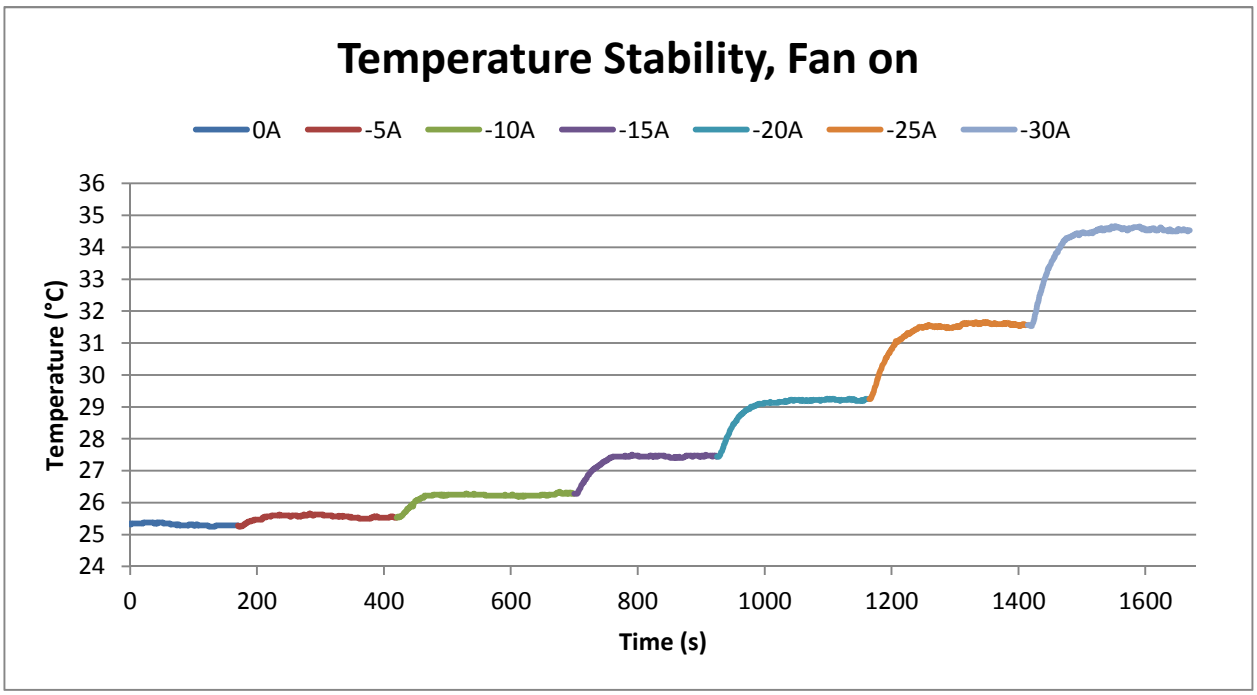


**Figure 11: Steady State Temperature, fan on**

## 6.2 Maximum Error Analysis

In order to set our design goals we identified the main influences of error.

- Input offset current of the INA250 ($I_{os}$)
- Gain error
- Common-mode rejection of the IAN250 (CMR)
- Power supply rejection of the INA250 (PSR)
- Shunt resistor tolerance

### 6.2.1 Errors at Small Values of Load Current

When the load current is small, there is very small voltage developed across the internal shunt of the INA250. Errors will therefore be dominated primarily by the input offset current for the device.

### 6.2.2 Errors at Large Values of Load Current

When the load current is large there are a greater number of contributors to overall error which are significant. Determining the errors with these parameters is described below. Unless otherwise noted, these error calculations are taken for a load current of 15 A (7.5 A to each device), 0-V common mode voltage, 16-V reference voltage, and 16-V supply voltage.

#### 6.2.2.1 Input Offset Error

The maximum error due to input offset current can be taken directly from the INA250A2 device specification. The maximum input offset current is given as 50 mA. This error is calculated with respect to a load current of 15 A through the board, which correlates to 7.5 A through each of the devices.

$$e_{I_{os}} = \frac{I_{os(max)}}{I_{load}} \times 100 = \frac{50mA}{7500mA} \times 100 = 0.6667\% \quad (3)$$

#### 6.2.2.2 Initial CMR Error

The maximum input offset error due to the common mode rejection of the INA250 is calculated by determining the actual common mode voltage as applied to the INA250 with reference to the ground pin of the INA250, and comparing that to the shunt voltage. For the INA250A2, the shunt voltage ($V_{shunt}$) is going to be equal to the load current times the nominal value for the integrated shunt (2mΩ). From the INA250 device specification the common mode rejection ratio typical value is given as 110 dB (3.6 µV/V). The offset voltage in the datasheet is specified with a common mode voltage of 12 V. The resulting common mode error is determined in equation 4.

$$e_{CMRR} = \frac{\left|V_{cm_{pds}} - V_{cm_{sys}}\right| \times CMRR_{INA250}}{V_{shunt}} \times 100 = \frac{|12V - 0V| \times 3.6\frac{\mu V}{V}}{7.5A \times .002\Omega} \times 100 = 0.253\% \quad (4)$$

#### 6.2.2.3 Initial PSR Error

Error due to PSRR can be calculated in a manner similar to CMRR. From the IAN250 device specification the specified power supply voltage for the input offset voltage specification is given as 5V. Any deviation from 5V applied between the INA250 VS pin and ground will result in an additional error. From the INA250 device specification the power supply rejection ratio maximum is given as 1mA/V. The PSR error is determined from equation 5.

$$e_{PSRR} = \frac{\left|V_{s_{pds}} - V_{s_{sys}}\right| \times PSRR_{INA250}}{I_{shunt}} \times 100 = \frac{|5V - 16V| \times 1\frac{mA}{V}}{7.5A} \times 100 = 0.1467\% \quad (5)$$

#### 6.2.2.4 Shunt Resistor and Gain Error

Both the shunt resistor tolerance and gain error are taken from the INA250A2 device specifications. The shunt resistor tolerance is 0.1% and the gain error is 0.3%.

#### 6.2.2.5 Total Error at High Load Current

Since there are two devices on this board, the total overall error is the sum of squares of the total device error for both INA250 devices. The input bias current is not included because it does not contribute significantly to overall error. The total error at a 15-A load current for the system is calculated in equations 6 and 7:

$$e_{device} = \sqrt{{e_{I_{os}}}^2 + {e_{CMRR}}^2 + {e_{PSRR}}^2 + {e_{gain}}^2 + {e_{shunt}}^2} = \sqrt{.6667^2 + .253^2 + .1467^2 + .3^2 + .1^2} = 0.7937\% \quad (6)$$

$$e_{total} = \sqrt{{e_{device}}^2 + {e_{device}}^2} = \sqrt{.7937^2 + .7937^2} = 1.1225\% \quad (7)$$

### 6.3 Measured Results Summary

**Table 4. Measured Performance Results**

| | Goal | Measured |
|---|---|---|
| **Relative Error ($I_{load}$= 15 A)** | 1.123% | 0.572% |
| **Relative Error ($I_{load}$= -15 A)** | 1.123% | 0.067% |
| **Relative Error ($I_{load}$= 30 A)** | 0.682% | 0.593% |
| **Relative Error ($I_{load}$= -30 A)** | 0.682% | 0.400% |

## 7 About the Author

Kareem Moulana (kareem.moulana@ti.com) is an Applications Engineer at Texas Instruments supporting current shunt monitors, temperature sensors, and optical devices. Kareem graduated from the University of Louisville's Speed School of Engineering, where he earned both a Bachelor of Science in Electrical Engineering with a minor in Mathematics as well as a Master of Science in Electrical Engineering.

## 8 Acknowledgements & References

### 8.1 Acknowledgements

The author wishes to acknowledge Jason Bridgmon, Rabab Itarsiwala and Mayrim Verdejo for their ideas, support and assistance with this TI Design.

# Appendix A.

## A.1 Electrical Schematic

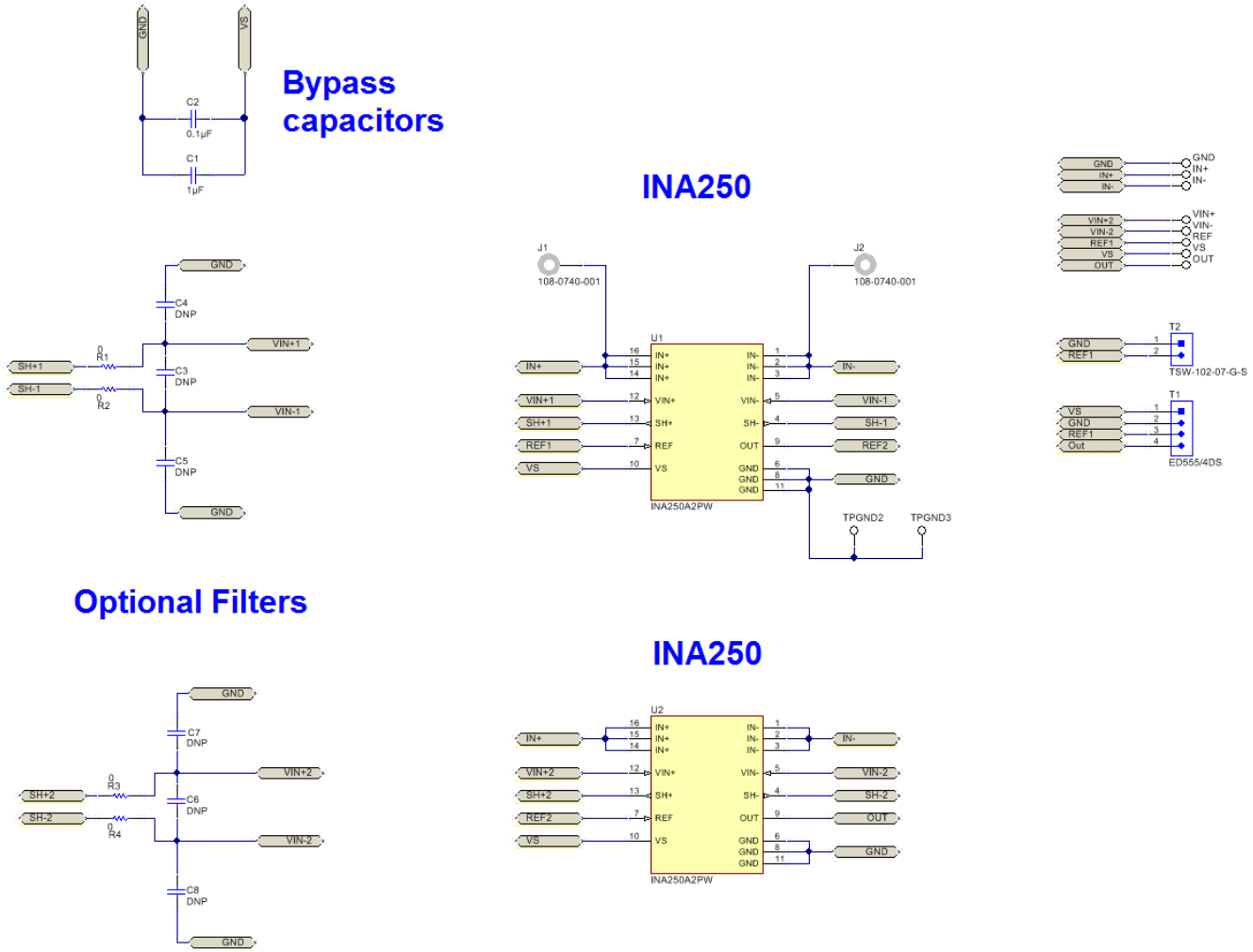


**Figure A-1: Electrical Schematic**

## A.2 Bill of Materials

Texas Instruments

# Bill of Materials

**TI DESIGNS**

TIDA-00614: 30A Range Bidirectional Current Shunt Monitor

| Item # | Quantity | Value | Designator | Description | Manufacturer | Part Number | Supplier Part Number |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1uF | C1 | CAP CER 1UF 50V 10% X7R 0805 | Samsung Electro-Mechanics America, Inc. | CL21B105KBFNNNE | 1276-1029-1-ND |
| 2 | 1 | 0.1uF | C2 | CAP CER 0.1UF 50V 10% X7R 0603 | TDK Corporation | C1608X7R1H104K080AA | 445-1314-1-ND |
| 3 | 2 | 0.1uF | C3, C6 (DNP) | CAP CER 0.1UF 25V 10% X5R 0603 | AVX Corporation | 06033D104KAT2A | 478-1244-1-ND |
| 4 | 4 | 0.1uF | C4, C5, C7, C8 (DNP) | CAP CER 0.1UF 25V 10% X7R 0805 | AVX Corporation | 08053C104KAT2A | 478-3755-1-ND |
| 5 | 8 | | GND, IN+, IN-, OUT, REF, VIN+, VIN-, VS | PC TEST POINT COMPACT SMT | Keystone Electronics | 5016 | 36-5016CT-ND |
| 6 | 4 | | H1, H2, H3, H4 | HEX STANDOFF 4-40 ALUMINUM 1" | Keystone Electronics | 2205 | 36-2205-ND |
| 7 | 4 | | H5, H6, H7, H8 | MACHINE SCREW PAN PHILLIPS 4-40 | B&F Fastener Supply | PMSSS 440 0025 PH | H703-ND |
| 8 | 2 | | J1, J2 | CONN JACK BANANA UNINS PANEL MOU | Cinch Connectivity Solutions Johnson | 108-0740-001 | J147-ND |
| 9 | 4 | 0Ω | R1, R2, R3, R4 | RES SMD 0.0 OHM JUMPER 1/10W | Panasonic Electronic Components | ERJ-3GEY0R00V | P0.0GCT-ND |
| 10 | 1 | | T1 | TERMINAL BLOCK 3.5MM 4POS PCB | On Shore Technology Inc. | ED555/4DS | ED1516-ND |
| 11 | 1 | | T2 | CONN HEADER 2POS .100" T/H GOLD | Samtec Inc. | HTSW-102-07-G-S | SAM8736-ND |
| 12 | 1 | | | SHUNT JUMPER .1" BLACK GOLD | 3M | 969102-0000-DA | 3M9580-ND |
| 13 | 2 | | U1,U2 | IC OPAMP CURR SENSE 36V 16TSSOP | Texas Instruments | INA250A2PW | 296-42177-5-ND |

**Figure A-2: Bill of Materials**

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