TI Designs
Analog Front End (AFE) for Sensing Temperature in Smart Grid Applications Using RTD

TI Designs

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Design Resources

TIDA-00110	Design Page
ADS1248	Product Folder
TPS7A1633	Product Folder
TCA6408A	Product Folder
TS3A5017D	Product Folder
CSD17571Q2	Product Folder
ADS1148	Product Folder

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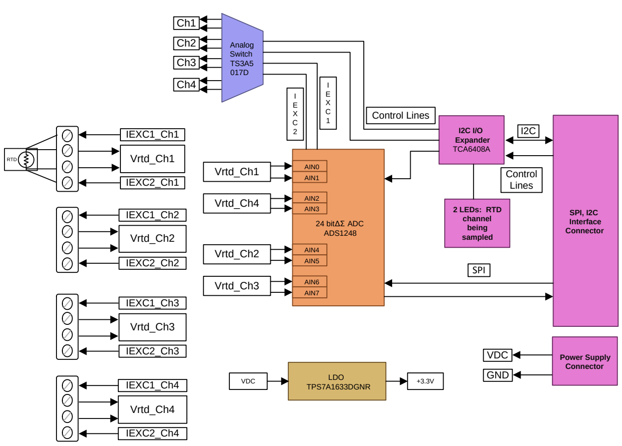
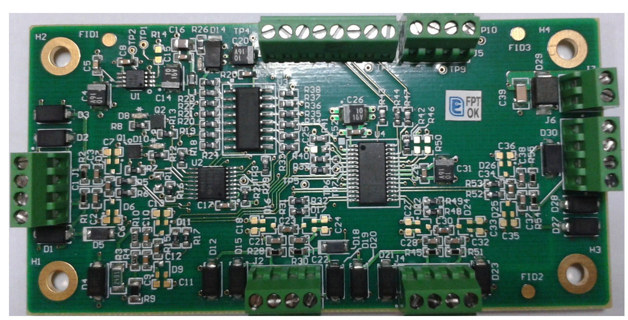
Design Features

- Based on the ADS1248 24-Bit Delta-Sigma (ΔΣ) ADC With Internal PGA and Selectable Gain up to 128
- Can Measure 2-, 3-, or 4-Wire RTD Inputs
- Meets Requirements for Smart Grid Applications
- Uses Ratiometric Measurement for Higher Accuracy
- Matched Current DACs for RTD Excitation
- Multiplexer (Analog Switch) to Switch Excitation Currents for Four RTD Inputs
- Accuracy < ±2°C Without Calibration for Pt100
- I2C I/O Expander for ADC Interface Control and Excitation Current Switching Provided (No External I/Os Required)

Featured Applications

- Protection Relays
- RTD Extension Modules for Protection Relay
- Remote Terminal Units





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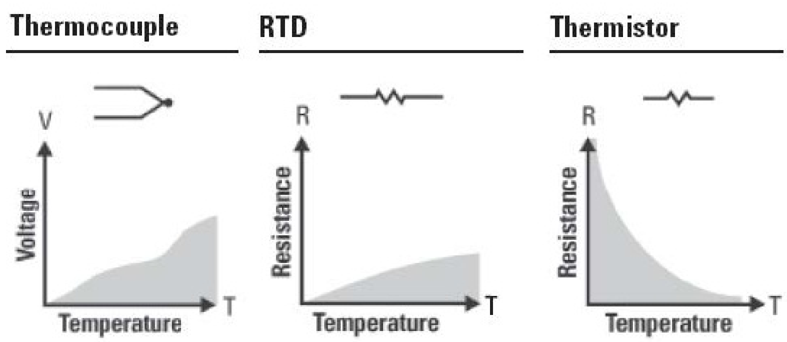
1 System Description

1.1 Resistance Temperature Detector

Temperature is one of the oldest known physical quantities. Temperature is the most essential factor that needs continuous measurement and monitoring in smart grid. Today, the industry demands accurate, repeatable, and reliable measurement of temperature, because temperature can have a significant impact on product cost, quality, efficiency, and safety.

Temperature sensors types include:

- Resistance temperature detector (RTD)
- Thermistor
- Thermocouple



Advantages

Thermocouple	RTD	Thermistor
• Self-powered	• Most stable	• High output
• Simple	• Most accurate	• Fast
• Rugged	• More linear than thermocouple	• Two-wire ohms measurement
• Inexpensive		
• Wide variety of physical forms		
• Wide temperature range		

Disadvantages

Thermocouple	RTD	Thermistor
• Non-linear	• Expensive	• Non-linear
• Low voltage	• Slow	• Limited temperature range
• Reference required	• Current source required	• Fragile
• Least stable	• Small resistance change	• Current source required
• Least sensitive	• Four-wire measurement	• Self-heating

Figure 1. Comparison of Different Temperature Sensors Used for Smart Grid Applications

The focus of this design is to measure temperature using RTD, a sensing element whose resistance changes with the temperature. The relationship between the resistance and temperature of an RTD is highly predictable, which allows accurate and repeatable temperature measurement over a wide range.

1.1.1 RTD Measurement

The basic principle of RTD measurement is based on the Ohm's law equation:

$$R = \frac{V}{I}$$

where

- R = Resistance of the RTD element
- I = Known excitation current
- V = Voltage across RTD element (1)

RTDs require constant current source for its excitation to produce a voltage output proportional to the resistance of the RTD. The resulting voltage output is measured by the analog-to-digital converter (ADC). The RTD voltage is amplified based on the requirement. Based on the measured voltage, the RTD resistance or temperature is calculated. Depending on the RTD type, different excitation currents can be used. The RTDs are available in different lead wire configurations: 2-, 3-, and 4-wire.

1.1.2 Ratiometric Measurement

A ratiometric approach guarantees more effective number of bits (ENOBs) as the noise in the IDAC reflects in the reference and as well as in the input and hence tends to cancel off. The effect of the IDAC current temperature drift also gets canceled off in this ratiometric topology.

ADC requires a reference voltage to convert the input voltage into a digital output. In most applications, this reference is fixed and generated either internal or external to the ADC. The voltage reference has direct influence on the accuracy of output. If the measurement can be configured such that the ADC result is a ratio of the input and a precision element such as a resistor, then much higher precision results can be obtained. In ratiometric configuration, the excitation current that flows through the RTD returns to ground through a low-side reference resistor, R_{REF}. The voltage developed across R_{REF} is fed into the positive and negative reference pins (REFP and REFN) of the ADC and ADS1248 is configured to use this external reference voltage V_{REF} for the analog-to-digital conversions. Select R_{REF} as a low-tolerance, low-drift resistor for accurate results.

The voltage drop across the RTD and R_{REF} resistors is produced by the same excitation source and the ADC output code is a relationship between the input voltage and the reference voltage. Therefore, errors as a result of the absolute accuracy of the excitation current and the errors because of excitation drift are virtually eliminated. In addition, the noise of the excitation source at the inputs is also reflected on the reference path of the ADC and, in this manner, cancels the noise. Therefore, the system becomes immune to variations in the excitation.

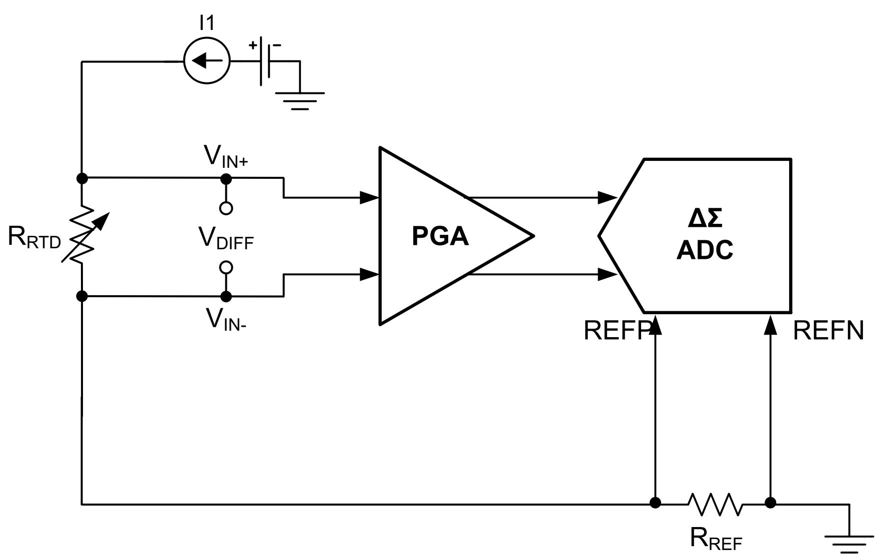


Figure 2. Simplified Circuit for RTD Ratiometric Measurement

$$ADC\_Output = \frac{V_{IN} \times GAIN \times (2^{23} - 1)}{V_{REF}} \tag{2}$$

$$ADC\_Output = \frac{IDAC \times RTD \times GAIN \times (2^{23} - 1)}{IDAC \times R_{REF}} \tag{3}$$

$$ADC\_Output = \frac{RTD \times GAIN \times (2^{23} - 1)}{R_{REF}} \tag{4}$$

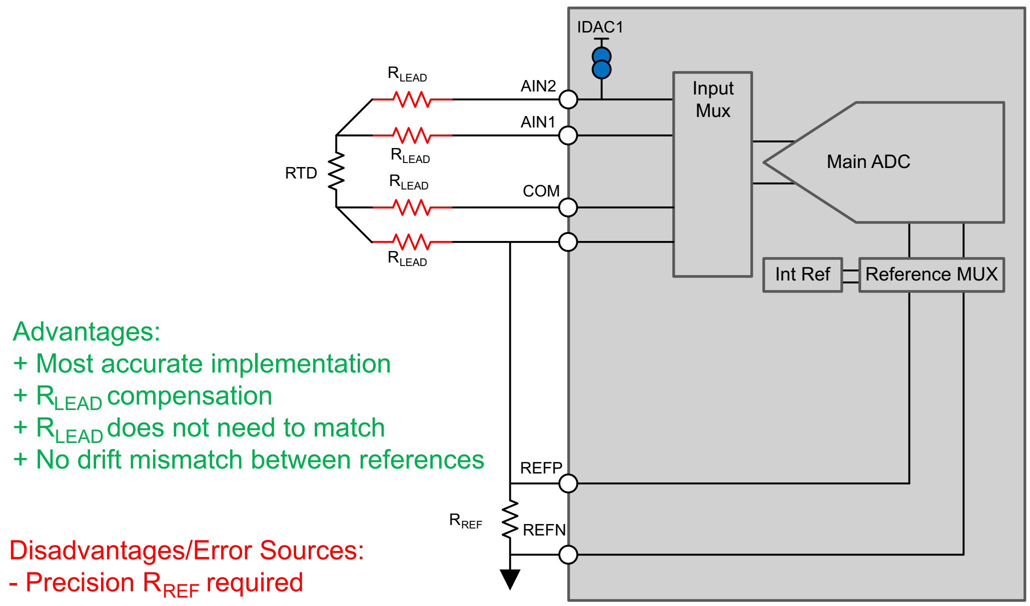


Figure 3. Ratiometric 4-Wire Operation

1.1.3 Connecting 2-, 3-, and 4-Wire RTD Inputs

This module is compatible with 2-, 3-, and 4-wire RTD inputs. The connection diagrams for connecting them to the module are shown in Figure 4. The user just needs to connect jumper wires externally as indicated by the red-colored wires. This arrangement does not call for any change in the hardware on the module and is quite useful when user can access only the interface connectors.

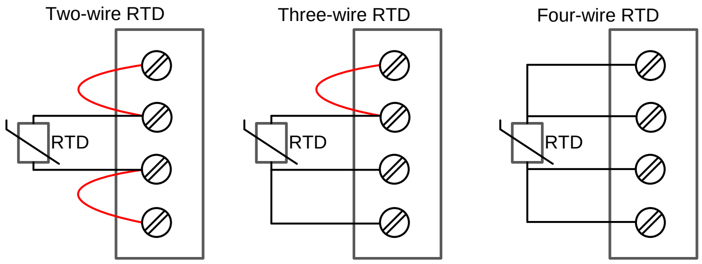


Figure 4. Different RTD Input Connections

Table 1. RTDs Used in Smart Grid

RTD TYPE	TEMPERATURE COEFFICIENT OF RESISTANCE (TCR) / °C
100-Ω platinum	0.00385
250-Ω platinum	0.00385
100-Ω nickel	0.00618
120-Ω nickel	0.00618
10-Ω copper	0.00427

Table 2 shows the resistance versus temperature for different types of RTDs.

Table 2. RTD Resistance versus Temperature

TEMPERATURE (°C)	RTD TYPE			
	Pt100	Ni100	Ni120	Cu10
300	212.02	—	439.44	—
200	175.84	223.20	303.46	16.78
100	138.50	161.80	200.64	12.90
90	134.70	154.90	191.64	12.51
80	130.89	148.30	182.84	12.12
70	127.07	141.70	174.25	11.74
60	123.24	135.30	165.90	11.35
50	119.40	129.10	157.74	10.97
40	115.54	123.00	149.79	10.58
30	11.67	117.10	142.06	10.19
20	107.79	11.20	134.52	9.81
10	103.90	105.60	127.17	9.42
0	100.00	100.00	120.00	9.04
–10	96.09	94.60	113.00	8.65
–20	92.16	89.30	106.15	8.26
–30	88.22	84.10	99.41	7.88
–40	84.27	79.10	92.76	7.49
–50	80.31	—	86.17	7.10

1.2 Protection Relay and Need for Temperature Sensing

Smart grid consists of the following sections:

1. Generation
2. Transmission
3. Distribution

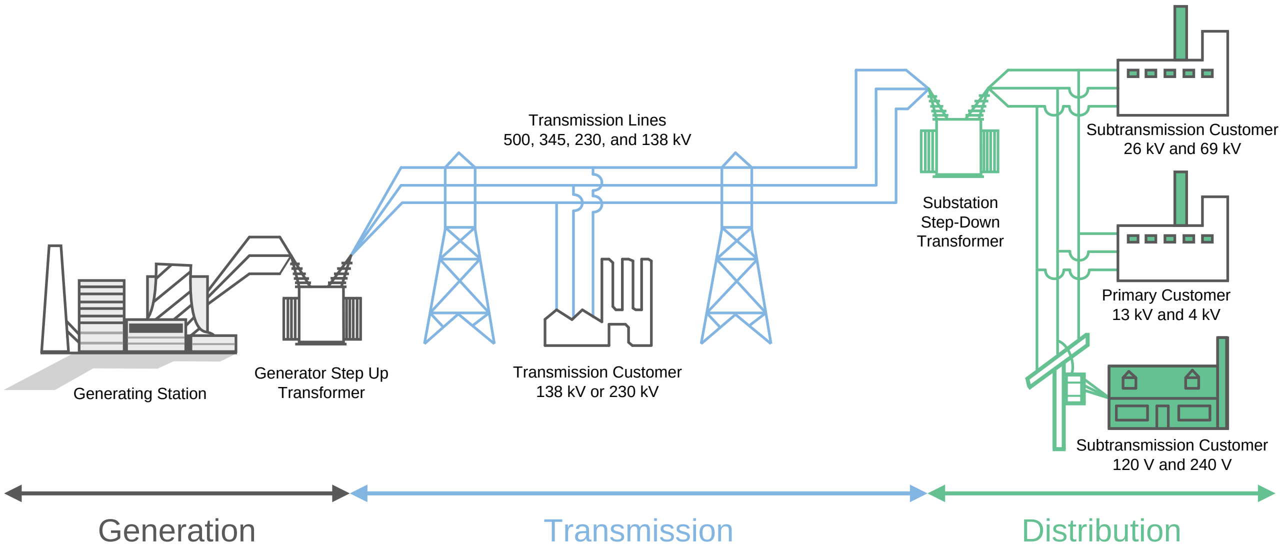


Figure 5. Smart Grid — Generation to Distribution

A typical smart grid system consists of generators for power, step-up transformers for transmission, step-down transformers for distribution, and loads consisting mainly of motors. The voltage and the power levels across the grid is very high, and any electrical faults on the system can lose a huge amount of capacity and revenue. To ensure the systems are protected against different electrical faults, use protection relays at different stages of the transmission system, such as

- Generator protection
- Transformer protection
- Distance protection
- Feeder protection
- Motor protection
- Bus bar protection

The basic purpose of a protection relay is to protect the grid in the event of a malfunction by monitoring the current and voltage on specific lines on the grid. The inputs into a protection relay are typically currents and voltages from a sensor on the line plus any communication from other related equipment on the grid network. The output would be signals to a circuit breaker (to turn open or close) and communication to the grid network. In case the protection relay detects a fault, the delay commands a breaker to open the line where the fault is detected, which protects everything down the line from the protection relay. The accurate measurement of the voltage, current, or other parameter like temperature pressure or vibration of a power system is a prerequisite to any form of control, ranging from automatic closed-loop control to the recording of data for statistical purposes. Measuring these parameters can be accomplished in a variety of ways, including the use of direct-reading instruments and electrical measuring transducers.

Protections relays measure the following parameters and based on the set threshold they protect:

1. Currents
2. Voltages
3. Temperature
4. Power direction

Most protection relays monitor temperature of the systems they protect.

Generator or Motor Protection

Generators are designed to run at a high load factor for a large number of years and permit certain incidences of abnormal working conditions. The machine and its auxiliaries are supervised by monitoring devices to keep the incidences of abnormal working conditions down to a minimum. Despite the monitoring, electrical and mechanical faults can occur, and the generators must be provided with protective relays, which, in case of a fault, quickly disconnect the machine from the system and, if necessary, completely shut down the machine. Thermal overload protection is one such protection. For motor protection, the relay monitors temperature of the following: motor winding, motor bearing, load bearing, and auxiliary winding.

Transformer Protection

Transformers are a critical and expensive component of the power system. Due to the long lead time for repair of and replacement of transformers, a major goal of transformer protection is to limit the damage to a faulted transformer. Temperature-based protection can aid this goal by identifying operating conditions that may cause transformer failure. Transformer protection relay monitors temperature of primary or secondary winding hot-spots, the oil at the bottom and top of the transformer, and the ambient air. An RTD input can also be used as a direct resistance measuring input for position tracking of an on-load tap changer.

The number of sensors depends on the size of the motor, generator, and transformer. Protection relays provide a certain number of RTDs. Many applications may need to monitor more RTDs and multiple motors, generators, or transformers using one protection relay. An RTD expansion module is used along with the protection relay to sense the temperature inputs, compute the temperatures and communicate the temperature values to the relay for protection. Different types of RTD can be used based on the applications. The accuracy of measurement for different sensors is expected to be the same and high. An accurate ADC is required to measure the temperature. An ADC with internal PGA ensures multiple types of RTD connection. A current source is required to excite the RTDs for measured. If the current source is integrated with the ADC, the complexity of design reduces and ensured better accuracy.

Some of the protections required in each segment are:

- For power generation: Generator protection, breaker protection, and transformer protections
- For transmission: Transformer protection, line voltage differential protection, and line distance protections
- For distribution: Transformer protection, motor protection, air circuit breakers, and molded case circuit breakers

Since a number of RTDs are connected to one expansion module or protection relay the conversion time of the ADC is important. The temperature is a slow varying signal, so the number of samples to be measured per second will be less. It is preferred that all the RTD inputs are samples at least once a second in a module that has 12 RTDs. Higher resolution ADCs with PGA, matched current source and radiometric measurement techniques, are used to improve accuracy.

TI has a large portfolio of ΔΣ ADCs that suits the requirements for RTD measurements. Additional to the resolution, TI ΔΣ ADCs have a high level of integration including current source, PGA, and reference. The ADCs consume a low amount of power.

Other advantages of ΔΣ ADCs include:

- Better noise performance for DC applications
- High resolution
- No active anti-aliasing filter required
- Good for "slow" signals
- Lower cost
- Lower power
- Small size
- Integration with:
  - PGA
  - Current sources
  - Sensor burn out detection
  - Temperature sensor

This design focuses on the following:

- Using TI ΔΣ ADCs for measuring temperature using RTD
- Measuring four RTD inputs
- Multiplexing current source to measure four RTD inputs
- Using internal PGA to achieve higher accuracy
- Using SPI to configure and read data from the ADC
- Using I2C I/O expander for /CS, START, /DRDY, excitation current selection, and LED indications

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NOTE: This design can be used inside a protection relay or in expansion modules. For safety, the user may need to isolate the RTD measurement sub system from the main processing system.

When there is a need for isolation, this TI design can be interfaced with the TI Design TIDA-00300. The TIDA-00300 provides isolation for SPI, I2C, and power inputs. The interface connectors are screw-type connectors enabling the boards to connect easily.

All the relevant design files such as schematics, BOM, layer plots, Altium files, firmware, and Gerber have also been provided to the user in Section 8.

2 Design Specifications

Typical requirements for TIDA-00110 are:

Table 3. System Specifications for TIDA-00110

PARAMETERS	SPECIFICATIONS AND FEATURES
Temperature sensing range	–50°C to 250°C
Measurement accuracy	< ±2°C
ADC resolution and type	24-bit, ΔΣ ADC with differential input
ADC interface for digital data	SPI compatible
RTD sensor type	2-, 3-, and 4-wire inputs
Number of RTD inputs	Four (4)
Current sources and excitation current range	Dual-matched current source with a current range programmable in defined steps in the range of 50 µA to 1.5 mA
Excitation current selection	Using dual single-pole quadruple-throw (4:1) analog switch
Multiplexer (analog switch) selection control	Using an I2C I/O expander
Display of measured values	GUI
Resistance measurement method	Ratiometric
DC input voltage	4 to 6 V
ADC power supply	3.3 V
Indication	LED indications for RTD input being sampled
Interface connectors	4-pin screw-type terminal block for each RTD input 4-pin screw-type terminal block for input power supply 8-pin screw-type terminal block for SPI and I2C interface

NOTE: For cost sensitive applications and applications that do not require wide temperature measurement, the ADS1148 16-bit ΔΣ ADC can be used. The ADS1148 is pin and footprint compatible with the ADS1248. Modify the firmware accordingly to use the ADS1148.

3 Block Diagram

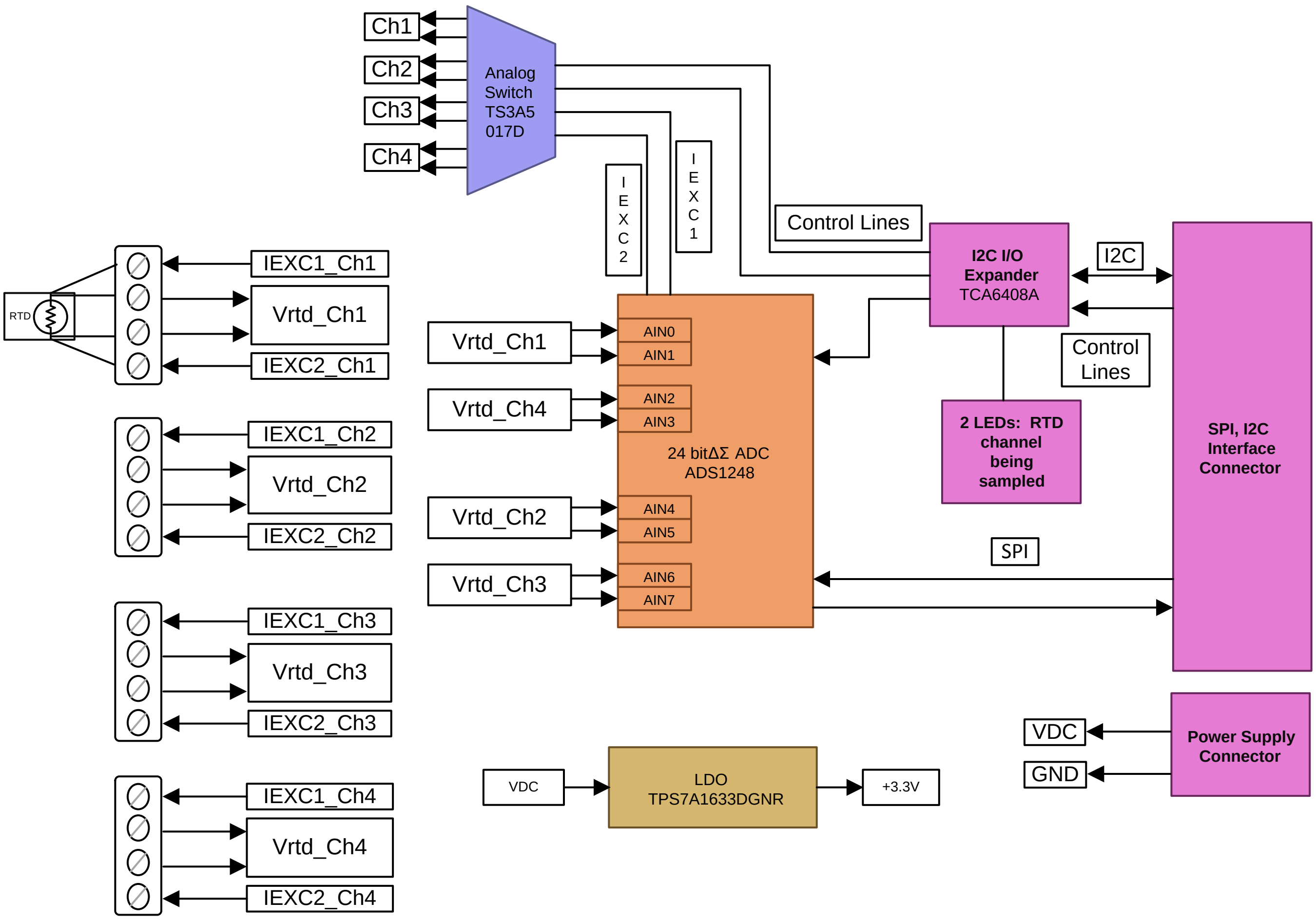

Figure 6. System Block Diagram

3.1 ADC

This design demonstrates measurement of four RTDs using a single ADS1248 ADC. ADS1248 is a highly-integrated, precision, 24-bit ADC.

ADS1248 has following features:

- Four differential inputs
- Matched current source for RTD excitation
- PGA with selectable gain up to 128
- Internal reference with provision to configure for external reference
- SPI for configuration and ADC samples reading
- /CS and START (conversion start) for control of sampling
- GPIOs for user usage

To communicate with the ADS1248, an SPI is provided on 8-pin screw-type terminal blocks. Four-pin screw-type terminal blocks are available for connecting the RTD inputs.

3.2 Dual 4:1 Analog Switch

This design uses dual-matched current source. This current is switched between four RTDs. TS3A5017D is used to switch excitation current between RTDs. The TS3A5017 is a dual single-pole quadruple-throw (4:1) analog switch that operates from 2.3 to 3.6 V and can handle analog signals.

3.3 I2C I/O Expander

I2C I/O expander is used for following:

- Switching of excitation current for RTD inputs
- For ADC control lines like /DRDY, START, /CS, /RESET
- To control LEDs (for visual indication)

This design uses TCA6408A, a low-voltage, 8-bit I2C I/O expander.

To communicate with the TCA6408A, the required I2C signals are extended to the 8-pin screw-type terminal block.

3.4 Power Supply

This design requires a 3.3-V supply. TPS7A1633 is used to generate 3.3 V. The TPS7A1633 is an ultra-low power, low-dropout (LDO) voltage regulator that offers the benefits of ultra-low quiescent current, high input voltage, and a miniaturized, high thermal-performance packaging. A 4-pin screw-type terminal block is provided to connect the external DC input.

3.5 LED Indicators

Two LEDs are provided to indicate the RTD input channel currently being scanned.

4 Circuit Design

4.1 ADC

Figure 7 and Figure 8 display the ADS1248 features:

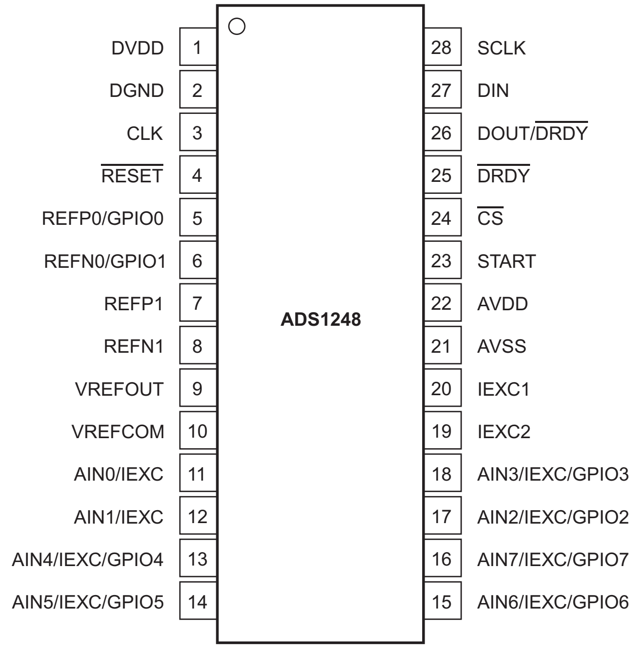

Figure 7. Pin Configuration of ADS1248

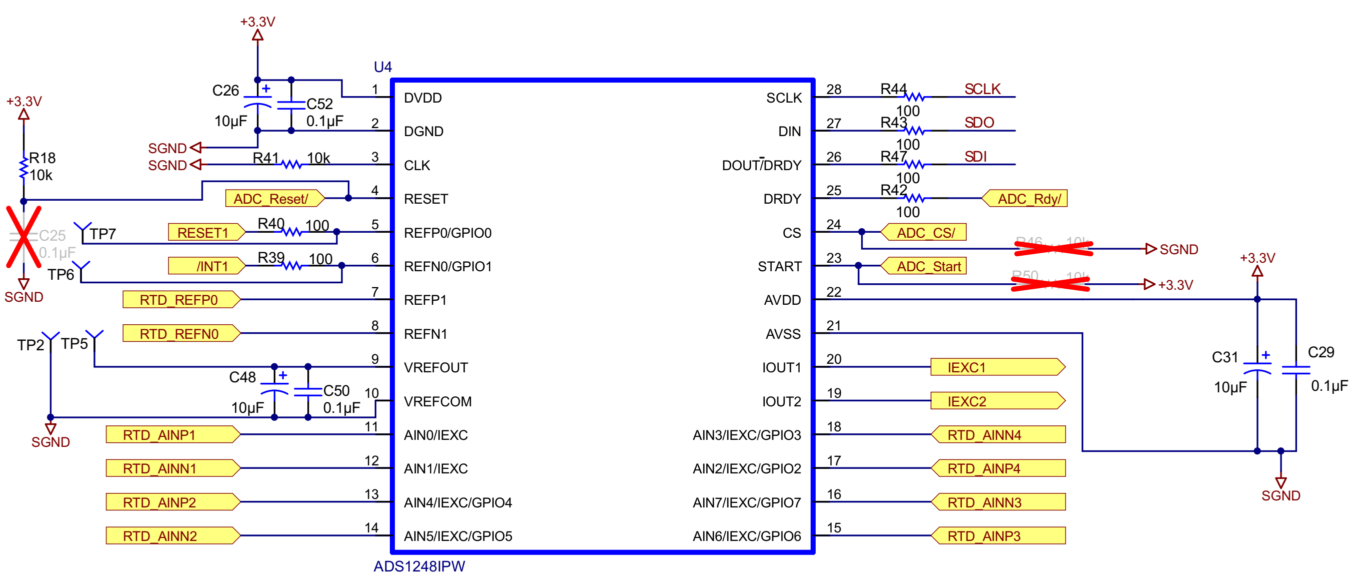

Figure 8. ADS1248 Pin Configuration

The four RTD inputs are connected to four differential inputs of the ADS1248.

The ADS1248 is a highly-integrated, precision, 24-bit ADC. The ADS1248 features an onboard, low-noise, programmable gain amplifier (PGA), a precision ΔΣ ADC with a single-cycle settling digital filter, and an internal oscillator. The ADS1248 also provides a built-in, very low-drift voltage reference with a 10-mA output capacity, and two matched programmable current digital-to-analog converters (DACs). The ADS1248 provides a complete front-end solution for temperature sensor applications including thermal couples, thermistors, and RTDs.

An input multiplexer supports four differential inputs for the ADS1248. In addition, the multiplexer has a sensor burnout detect, system monitoring, and general-purpose digital I/Os. The onboard, low-noise PGA provides selectable gains of 1 to 128. The ΔΣ modulator and adjustable digital filter settle in only one cycle, for fast channel cycling when using the input multiplexer, and support data rates up to 2 kSPS.

Internal reference with provision to configure for external reference is available in ADS1248.

The voltage reference for the ADS1248 is the differential voltage between REFP and REFN:
$V_{REF} = V_{REFP} – V_{REFN}$

For the ADS1248, there is a multiplexer that selects the reference inputs. The reference input uses a buffer to increase the input impedance as with the analog inputs, REFP0 and REFN0 can be configured as digital I/Os on the ADS1248. This design uses external reference.

The ADS1248 is rated over the extended specified temperature range of –40°C to 105°C.

Some of the highlighted features of ADS1248 are:

- 24 bits, no missing codes
- Data output rates up to 2 kSPS
- Single-cycle settling for all data rates
- Four differential or seven single-ended inputs
- Low-noise PGA: 48 nV at PGA = 128
- Matched current source DACs
- Very low drift internal voltage reference: 10 ppm/°C (max)
- Sensor burnout detection
- Eight general-purpose I/Os
- Internal temperature sensor
- Power supply and V_{REF} monitoring
- Self and system calibration
- SPI compatible
- Analog supply: unipolar (2.7 to 5.25 V)
- Digital supply: 2.7 to 5.25 V

4.1.1 3-Wire RTD Calculations

The ADS1248 integrates all necessary features (such as dual-matched programmable current sources, buffered reference inputs, PGA, and so forth) to ease the implementation of ratiometric 2-, 3-, and 4-wire RTD measurements. The 3-wire RTD configuration is most commonly used for industrial temperature sensors. Figure 9 shows a typical implementation of a ratiometric 3-wire RTD measurement.

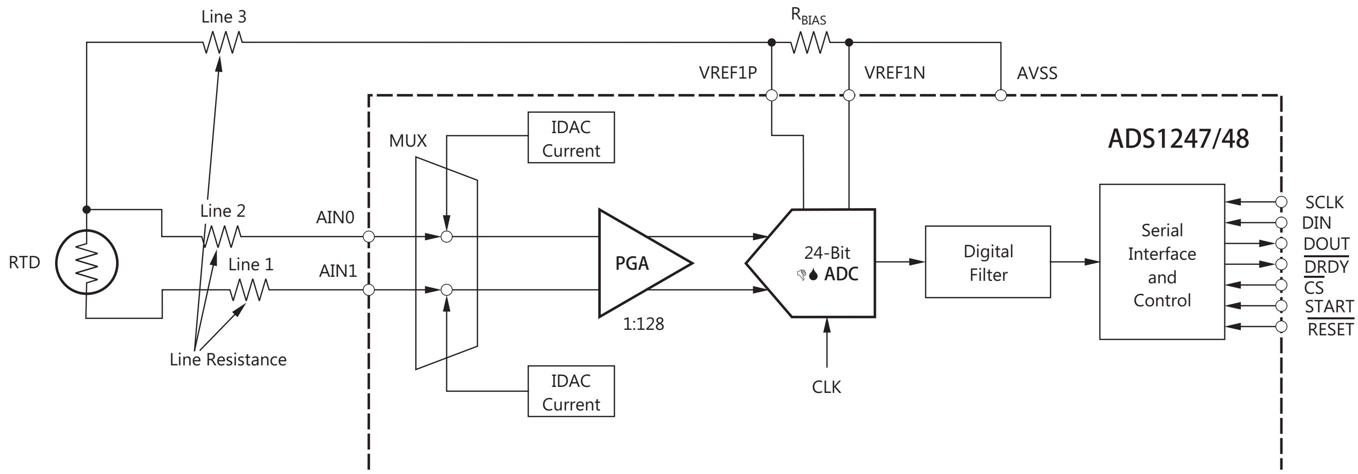

Figure 9. 3-Wire RTD Measurement Circuit Diagram

The ADS1248 features two IDAC current sources capable of outputting currents from 50 µA to 1.5 mA. IDAC1 is routed to one of the excitation leads of the RTD while IDAC2 is routed to the second excitation lead as shown in Figure 9 by appropriate setting of IDAC1 and IDAC2 in the firmware. Both currents have the same value, which is programmable. The design of the ADS1248 ensures that both IDAC values are closely matched, even across temperature.

4.1.1.1 R_{REF} and PGA Gain

The resistance of the Pt100 changes from 80.31 Ω at –50°C to 194.07 Ω at 250°C. The line resistance R_{LEAD} depends on the distance of the sensor from the measurement setup. Assuming R_{LEAD} equals 5 Ω, the positive resistance swing is from 100 to 194.07 Ω, which is about 90.07 Ω. The negative resistance swing is from 100 to 80.31 Ω, which is about 19.69 Ω. The IDAC current must be 1 mA or less to minimize the self-heating error. The IDAC current chosen here is 500 µA. Then, maximum and minimum input voltages to the PGA are 194.07 Ω × 500 µA = 97.04 mV and 80.31 Ω × 500 µA = 40.15 mV, respectively. The external reference resistor R_{REF} serves two purposes firstly it decides the external reference voltage for ADC and secondly, it also determines the input common mode voltage of the PGA. Set the common mode voltage around mid-supply (AVDD – AVSS) / 2 = (3 V – 0 V) / 2 = 1.65 V. Therefore, the reference voltage chosen here is 2 V, which also depends on easily available resistance value and excitation current. The sum of both currents flows through a precision low-drift reference resistor, R_{REF}. The voltage, V_{REF}, generated across the reference resistor is given in Equation 5:

$$V_{REF} = (IDAC1 + IDAC2) \times R_{REF} \tag{5}$$

Because IDAC1 = IDAC2 = 500 µA:

$$V_{REF} = 2 \times IDAC1 \times R_{REF} \tag{6}$$

Solving for R_{REF}:

$$R_{REF} = \frac{V_{REF}}{2 \times IDAC1} = \frac{2\ V}{2 \times 500\ \mu A} = 2\ K\Omega \tag{7}$$

For the required gain:

$$GAIN_{PGA} = \frac{V_{REF}}{VIN_{MAX}} = \frac{2V}{97.04\,mV} = 20.6 \tag{8}$$

The nearest gain that can be programmed is 16.

4.1.1.2 Common-Mode Voltage Compliance Check

The signal of an RTD is of a pseudo-differential nature, where the negative input must be biased at a voltage other than 0 V and the positive input can then swing up to 97.04 mV above the negative input.

The allowed common-mode input voltage range is as highlighted in Figure 10 (taken from the ADS1248 datasheet [8]):

PARAMETER	CONDITIONS	ADS1246, ADS1247, ADS1248 MIN	TYP	MAX	UNIT
ANALOG INPUTS					
Full-scale input voltage (V_{IN} = ADCINP – ADCINN)			$\pm V_{REF}/PGA$ (1)		V
Common-mode input range		$AVSS + 0.1V + \frac{(V_{IN})(Gain)}{2}$		$AVDD - 0.1V - \frac{(V_{IN})(Gain)}{2}$	V

Figure 10. Common-Mode Input Range Equation

Assume that IDAC1 = IDAC2 and RL (R_{LEAD}) = 5 Ω (depending on length of lead wires).

Calculating V_{CMI} from the equations highlighted in Figure 10:
Placing AVSS = 0 V, V_{IN} = 97.04 mV, Gain = 16, and AVDD = 3.3 V in the equations shown in Figure 10:

V_{CMI_MIN} = 0.876 V and V_{CMI_MAX} = 2.423 V

Now, the common-mode input voltage actually set by the design can be given as:

$$V_{CMI} = (IDAC \times R_{LEAD}) + \frac{IDAC \times R_{RTD}}{2} + 2 \times IDAC \times (R_{LEAD} + R_{REF}) \tag{9}$$

Placing IDAC = 500 µA, R_{LEAD} = 5 Ω, R_{RTD} = 194.07 Ω, and R_{REF} = 2 kΩ in Equation 9:
$V_{CMI\_MIN\_APPLIED}$ = 2.027 V

Placing IDAC = 500 µA, R_{LEAD} = 5 Ω, R_{RTD} = 194.07 Ω, and R_{REF} = 2 kΩ in Equation 9:
$V_{CMI\_MAX\_APPLIED}$ = 2.056 V

Here, $V_{CMI\_MIN\_APPLIED} > V_{CMI\_MIN}$ and $V_{CMI\_MAX\_APPLIED} < V_{CMI\_MAX}$

This value is well within the maximum allowed common-mode input voltage range.

4.1.2 Noise Considerations and Input Filter

RTD voltage output signals are typically in millivolt range which makes them susceptible to noise. A first-order differential and common-mode RC filter (R_{F1}, R_{F2}, C_{DIF1}, C_{CM1}, and C_{CM2}) is placed on the ADC inputs, as well as on the reference inputs (R_{F3}, R_{F4}, C_{DIF2}, C_{CM3}, C_{CM4}) to eliminate high-frequency noise in RTD measurements. For best performance, it is recommended to match the corner frequencies of the input and reference filters. More detailed information on matching the input and reference filters can be found in application report *RTD Ratiometric Measurements and Filtering Using the ADS1148 and ADS1248*.[2]

The differential filters chosen for this application were designed to have a –3-dB corner frequency at least 10 times larger than the bandwidth of ADC. The selected ADS1248 sampling rate of 20 SPS results in a –3-dB bandwidth of 13.1 Hz. The cut off frequency chosen for this design is higher to account for faster sampling rate. For proper operation, the differential cutoff frequencies of the reference and input low-pass filters must be well matched. Matching the frequencies and filters can be difficult because as the resistance of the RTD changes over the span of the measurement, the filter cutoff frequency changes as well. To mitigate this effect, the two resistors used in the input filter (RI1 and RI2) were chosen to be more than an order of magnitude larger than the RTD. Limiting the resistors to at most 20 kΩ to keep DC offset errors low due to input bias current.

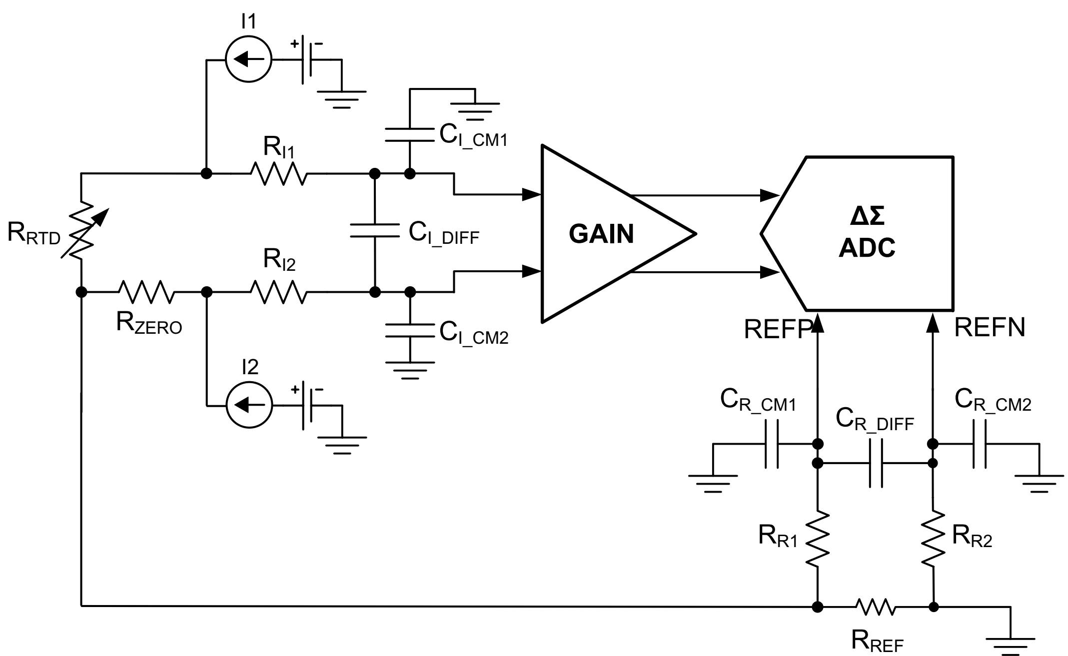

Figure 11. Common Mode and Differential Mode Filters on RTD Input and Reference

$R_{I1} = R_{I2} = 4.12\ k\Omega$ and $C_{I\_DIFF} = 0.047\ \mu F$

The –3-dB cutoff frequency of differential input filter at a 186-Ω RTD resistance (at mid-scale temperature) can be calculated as given in Equation 10.

$$F_{-3dB\_I\_DIFF} = \frac{1}{2 \times \pi \times C_{I\_DIFF} \times (R_{I1} + R_{RTD} + R_{I2})}$$

$$F_{-3dB\_I\_DIFF} \approx 402.1\,\text{Hz} \quad (10)$$

To ensure that mismatch of the common-mode filtering capacitors is not translated to a differential voltage, the common-mode capacitors (C_{I_CM1} and C_{I_CM2}) were chosen to be 10 times smaller than the differential capacitor. This results in a common-mode cutoff frequency that is roughly 10 times larger than the differential filter, making the matching of the common-mode cutoff frequencies less critical.

$C_{I\_CM1} = C_{I\_CM2} = 4700$ pF

Although it is not always possible to exactly match the corner frequencies of all the filters, a good compromise is to attempt to balance the corner frequencies of the input path differential filter and the reference path differential filter because these filters have a dominant effect in the performance.

$R_{R1} = R_{R2} = 4.7\ k\Omega$ and $C_{R\_DIFF} = 0.033\ \mu F$

The –3-dB cutoff frequency of differential reference filter can be calculated as given in Equation 11:

$$F_{-3dB\_R\_DIFF} = \frac{1}{2 \times \pi \times C_{R\_DIFF} \times (R_{R1} + R_{REF} + R_{R2})}$$

$$F_{-3dB\_R\_DIFF} \approx 405.83\ \text{Hz} \quad (11)$$

To ensure that mismatch of the common-mode filtering capacitors is not translated to a differential voltage, the common-mode capacitors (C_{R_CM1} and C_{R_CM2}) were chosen to be 10 times smaller than the differential capacitor. This results in a common-mode cutoff frequency that is roughly 10 times larger than the differential filter, making the matching of the common-mode cutoff frequencies less critical.

$C_{R\_CM1} = C_{R\_CM2} = 3300$ pF

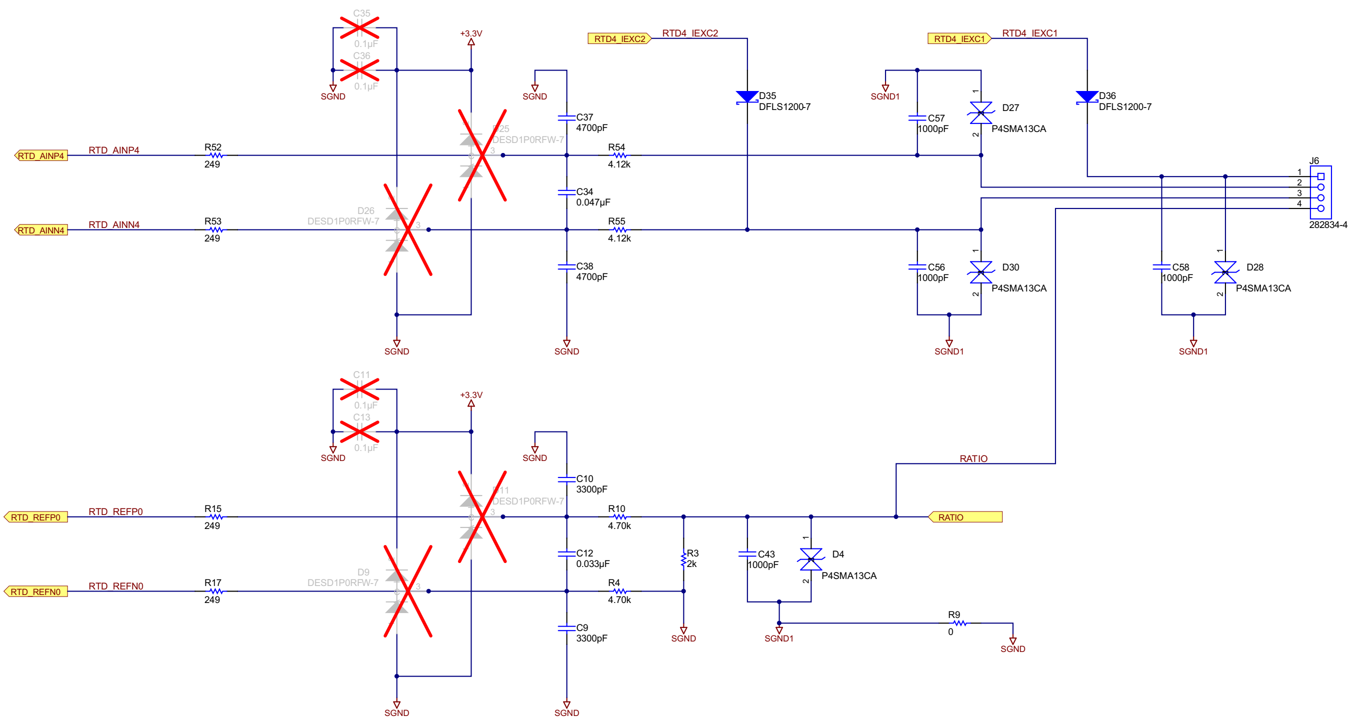

Figure 12. Common-Mode and Differential-Mode Filters Implemented in Design for RTD

Furthermore, before taking sensor measurement, the user must ensure that the external RC filters settle down to ½ LSB after activating the excitation current sources. It may be ensured by implementing software delay for several RC time constants. For 24-bit resolution measurement, after exciting the sensor, the user must wait up to 17-RC filter time constants for consistent measurements.

Table 4. 4-Pin Terminal Block TH Connector for External RTD Input

RTD	CONNECTOR ON THE BOARD
RTD1	J1
RTD2	J2
RTD3	J4
RTD4	J6

Figure 13 shows the RTD connectors on the board.

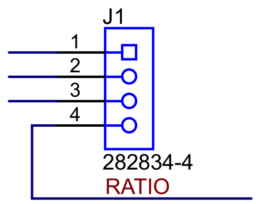

Figure 13. J1 Connector of RTD1

The ADS1248 has a simple SPI-compatible serial interface to communicate with the host. In this design, the SPI is communicating at 2Mbps.

Figure 14 shows the 8-pin terminal block for the SPI and I2C interface.

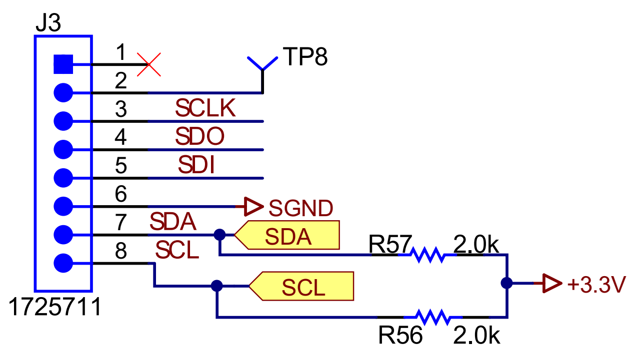

Figure 14. J3 Connector for SPI and I2C Interface With External Devices

4.2 Multiplexer

TS3A5017D is used to switch excitation current for all the RTDs. The TS3A5017 is a dual single-pole, quadruple-throw (4:1) analog switch that is designed to operate from 2.3 to 3.6 V. This device can handle both digital and analog signals, and signals up to V_+ can be transmitted in either direction.

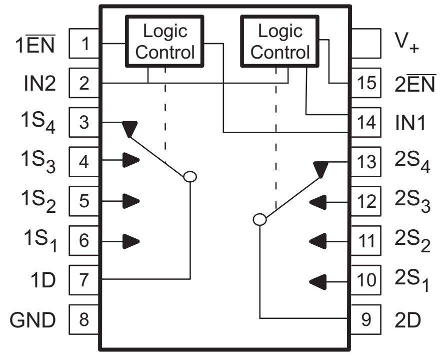

Figure 15. Pin Configuration View of TS3A5017D

Figure 16 shows excitation current multiplexing connections:

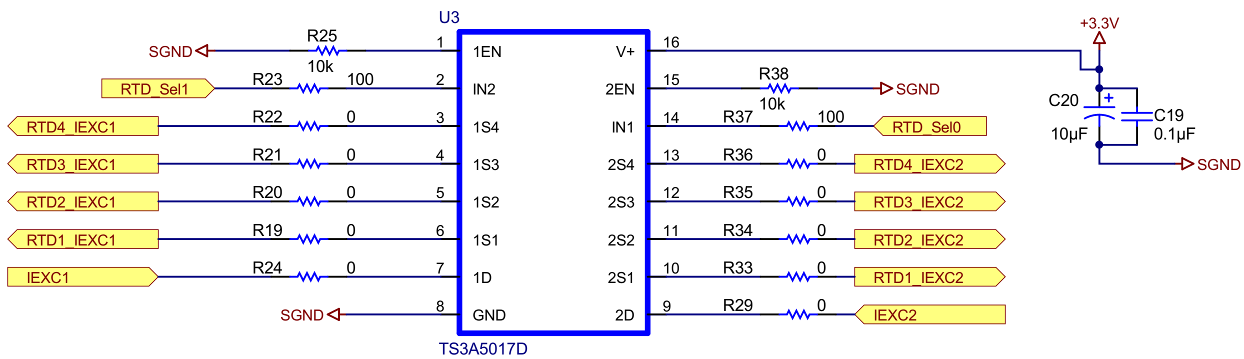

Figure 16. Multiplexer Section

Some of the highlighted features of TS3A5017D are:

- Isolation in the powered-down mode, $V_+ = 0$
- Low on-state resistance
- Low charge injection
- Excellent on-state resistance matching
- Low total harmonic distortion (THD)
- 2.3- to 3.6-V single-supply operation
- Latch-up performance exceeds 100 mA per JESD 78, Class II

4.3 I2C I/O Expander

This design uses the TCA6408A, a low-voltage 8-bit I2C I/O expander.

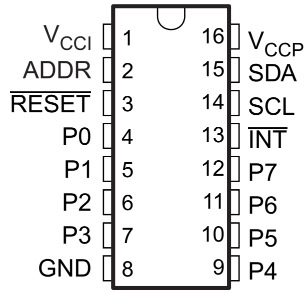

Figure 17. Pin Configuration of TCA6408A

The TCA6408A performs the following actions in this design:

- Controls switching of excitation current between four channels of RTD
- Communicates with ADC control lines /DRDY, START, /CS, and /RESET
- Controls LEDs (for visual indication)

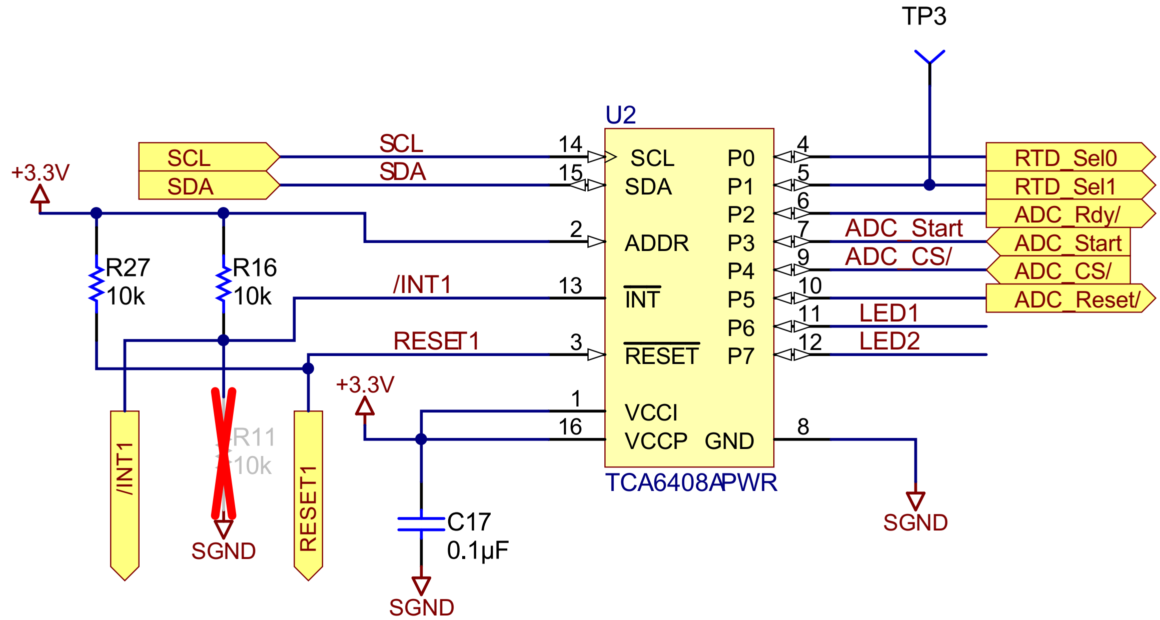

Figure 18. I2C I/O Expander

This 8-bit I/O expander for the I2C provides general-purpose remote I/O expansion through the I2C interface [serial clock (SCL) and serial data (SDA)].

Some of the highlighted features of the TCA6408A are:

- Operating power-supply voltage range of 1.65 to 5.5 V
- I2C to parallel port expander
- Low standby current consumption of 1 μA
- Schmitt-trigger action allows slow input transition and better switching noise immunity at the SCL and SDA inputs V_{HYS} = 0.33 V typical at 3.3 V
- 5-V tolerant I/O ports
- Active-low reset (RESET) input
- Open-drain active-low interrupt (INT) output
- 400-kHz fast I2C bus
- I/O configuration register
- Polarity inversion register
- Internal power-on reset
- Power up with all channels configured as inputs
- No glitch on power up
- Noise filter on SCL/SDA inputs
- Latch-up performance exceeds 100 mA per JESD 78, Class II
- ESD protection exceeds JESD 22
  – 2000-V human-body model (A114-A)
  – 1000-V charged-device model (C101)

4.4 Power Supply

The TPS7A1633 is an ultra-low power, LDO voltage regulator that offers the benefits of ultra-low quiescent current, high input voltage and miniaturized, high thermal-performance packaging.

The TPS7A1633 is designed for continuous or sporadic (power backup) battery-powered applications where ultra-low quiescent current is critical to extending system battery life.

The TPS7A1633 offers an enable pin (EN) compatible with standard CMOS logic and an integrated open drain active-high power good output (PG) with a user-programmable delay. These pins are intended for use in microcontroller-based, battery-powered applications where power-rail sequencing is required.

Not only can this device supply a well-regulated voltage rail, but it can also withstand and maintain regulation during voltage transients. These features translate to simpler and more cost-effective, electrical surge-protection circuitry

Table 5. Critical Parameters of TPS7A1633

PARAMETER	VALUE
Iout (Max) (A)	0.1
Output options	Fixed output
Vin (Min) (V)	3
Vin (Max) (V)	60
Fixed output options (V)	3.3
Vout (Min) (V)	3.3
Vout (Max) (V)	3.3
Iq (Typ) (mA)	0.005
Vdo (Typ) (mV)	60
Accuracy (%)	2
PSRR at 100 KHz (dB)	26

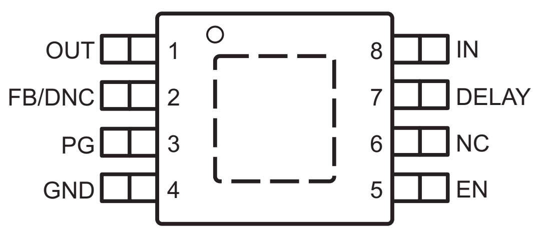

Figure 19. Pin Configuration of TPS7A1633

Figure 20 shows the implementation of a 3.3-V power supply using the TPS7A1633 LDO.

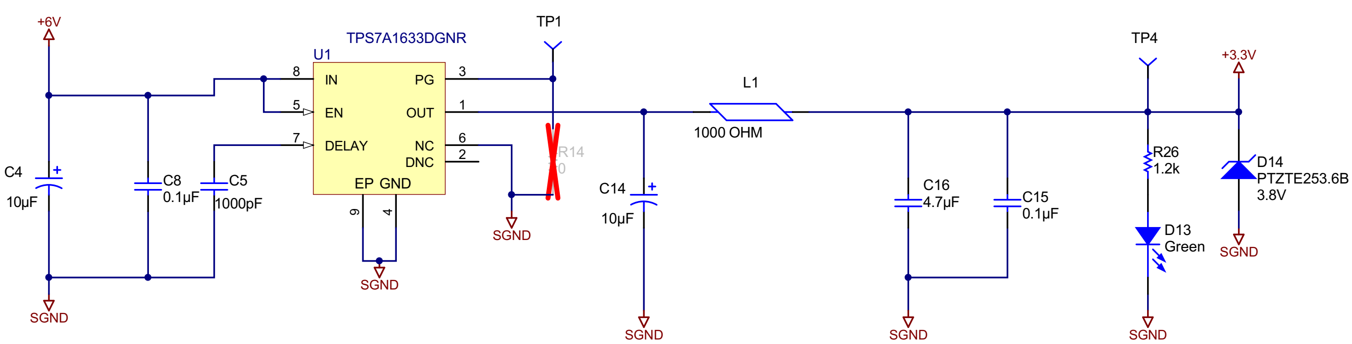

Figure 20. TPS7A1633 Section of the TIDA-00110 Schematic

Figure 21 shows the 4-pin terminal block for the power supply input.

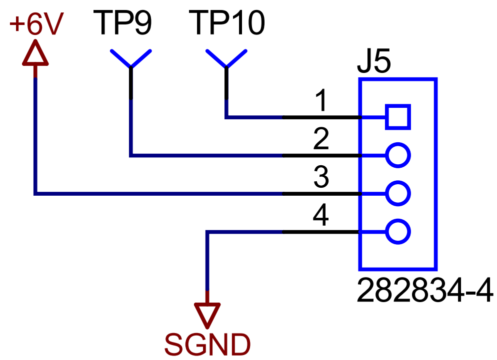

Figure 21. DC Input Connector

4.5 LED Indicators

The LEDs indicate the present status of the RTD channel that is beg scanned. The indication logic is as shown in Table 6.

Table 6. LED Indicators

PRESENT SCANNING	LED1 (D8) STATUS	LED2 (D10) STATUS
Channel 1	Toggle	Toggle
Channel 2	OFF	ON
Channel 3	ON	OFF
Channel 4	ON	ON

4.6 Tiva™ C Series LaunchPad™ Interface

The Tiva C Series LaunchPad (EK-TM4C123GXL) is a low-cost evaluation platform for ARM® Cortex™-M4F-based microcontrollers. The Tiva C Series LaunchPad design highlights the TM4C123GH6PMI microcontroller USB 2.0 device interface, hibernation module, and motion control pulse-width modulator (MC PWM) module. The Tiva C Series LaunchPad also features programmable user buttons and an RGB LED for custom applications. The stackable headers of the Tiva C Series LaunchPad BoosterPack™ XL interface demonstrate how easy it is to expand the functionality of the Tiva C Series LaunchPad when interfacing to other peripherals on many existing BoosterPack add-on boards as well as future products. Figure 22 shows a photo of the Tiva C Series LaunchPad.

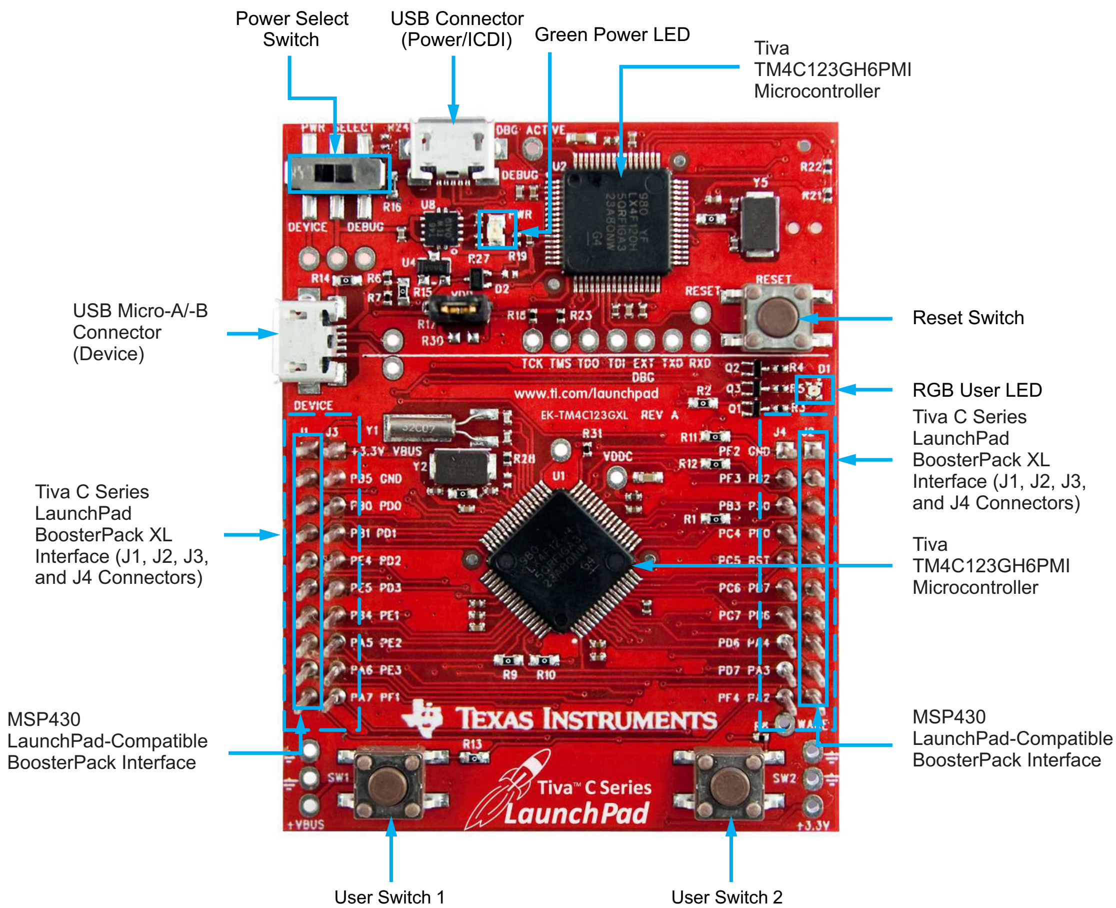

Figure 22. Tiva C Series TM4C123G LaunchPad Evaluation Board

4.7 PCB Design Guidelines

- An SMD ceramic bypass capacitor of approximately 0.1 µF in value is recommended for all the digital ICs. Should it be required to use leaded components, keep leads as short as possible to minimize lead inductance.
- A continuous ground plane is ideal for providing a low-impedance signal return path as well as generating the lowest EMI signature by reducing phenomena such as unintended current loops.
- Should a continuous ground plane not be possible, it is important to minimize the length of the trace connecting VCC and ground.
- PCB material: Standard Flame Retardant 4 (FR-4) epoxy-glass as printed-circuit board (PCB) material is preferred for industrial applications with a speed < 100 Mhz. FR-4 meets the requirements of Underwriters Laboratories UL94-V0 and is preferred over cheaper alternatives due to its lower dielectric losses at high frequencies, less moisture absorption, greater strength and stiffness, and its self-extinguishing, flammability characteristics.
- Trace routing: Use 45° bends (chamfered corners), instead of right-angle (90°) bends. Right-angle bends increase the effective trace width, and thus the trace impedance. This creates additional impedance mismatch, which may lead to higher reflections.

5 Software Description

For software description and code examples for TIDA-00110, please see *TIDU575: Software Code Examples for TIDA-00110*.

6 Test Setup

Tools and equipment used to test ADC measurement accuracy:

- Yokogawa Model GS610 Source Measure Unit with accuracy: ±0.02% (DC voltage generation)
- Agilent 34401A 6½-Digit Multimeter for measuring resistance in four-wire method and measuring mV
- 0.01% tolerance high precision resistor to simulate RTD resistance

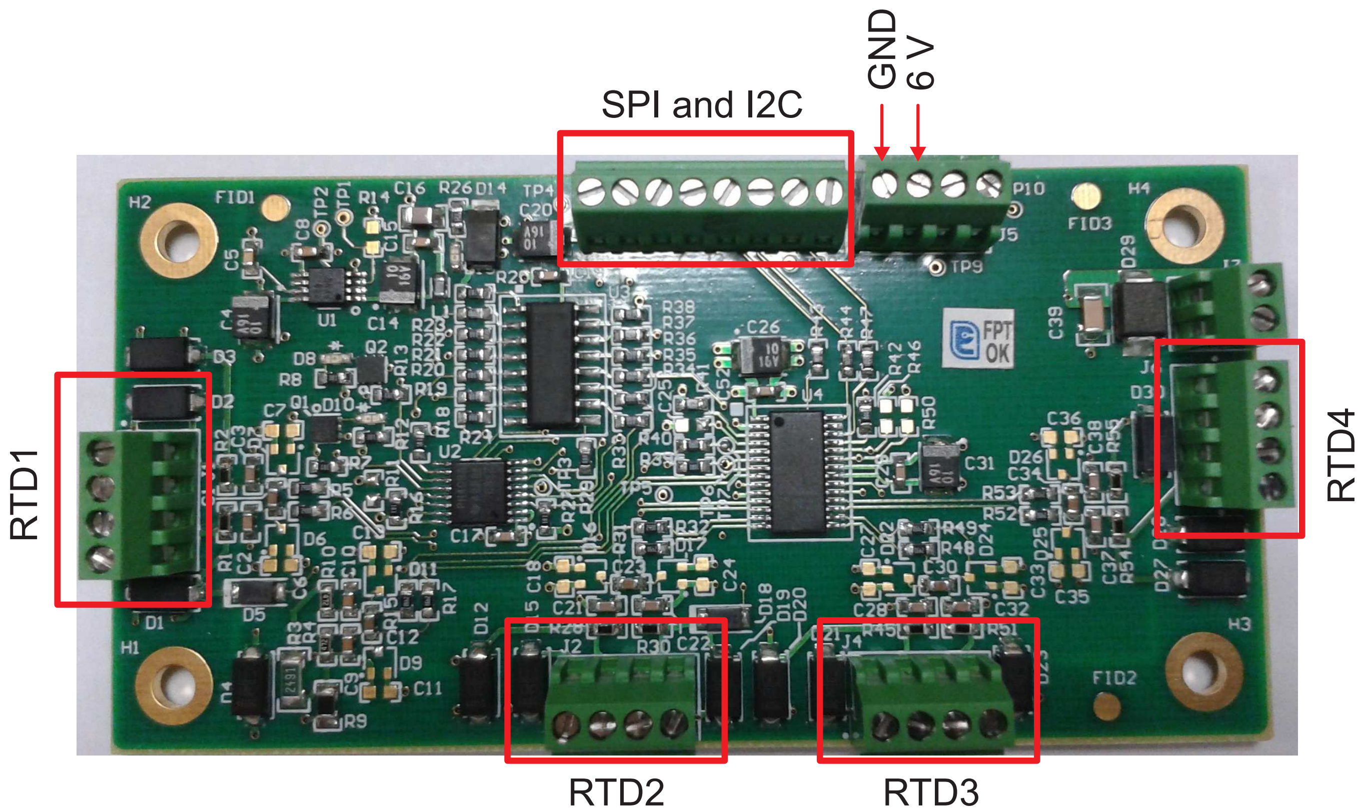

Figure 23. Test Setup for TIDA-00110

For Pt100 RTD, Table 7 shows resistance and respective voltage (mV) for different temperatures.

Table 7. Temperature versus Voltage Across RTD

TEMPERATURE (°C)	RESISTANCE (Ω)	EXPECTED VOLTAGE DROP WITH 500-µA EXCITATION CURRENT (mV)
–50	80.3068	40.15
0	100.0000	50.00
50	119.3951	59.70
100	138.5000	69.25
150	157.3149	78.66
200	175.8396	87.92
250	194.0743	97.04

7 Test Results

7.1 ADC Linearity

To check the linearity of ADS1248, a DC mV input signal is applied using the Yokogawa Model GS610 Source. ADC bit counts (ADC_CODE) are read for RTD channels 1 to 4. ADC counts are converted to V_{IN} using Equation 12:

$$V_{IN} = 1\ \text{LSB} \times (\text{ADC\_CODE})_{\text{DEC}} = \frac{2 \times V_{REF} \times (\text{ADC\_CODE})_{\text{DEC}}}{\text{GAIN} \times (2^{23} - 1)} \qquad (12)$$

Use V_{REF} = 2.048 V, GAIN = 16, and ADC_CODE = ADC readings for each RTD channel.

Table 8. Channel 1: Linearity Performance

$V_{APPLIED}$ (mV)	$V_{CHANNEL1}$ (mV) (WITHOUT GAIN MULTIPLICATION)	$CHANNEL1_{ERROR}$ (AFTER GAIN MULTIPLICATION)
24.972	24.95766	0.07%
29.972	29.94252	0.03%
34.969	34.9265	0.01%
36.969	36.92699	0.01%
38.970	38.9221	0.01%
40.969	40.92225	0.01%
42.969	42.9146	0.00%
44.969	44.90884	–0.01%
46.968	46.91064	0.01%
48.967	48.90668	0.01%
50.970	50.90246	0.00%
52.970	52.89703	–0.01%
54.967	54.89291	–0.01%
56.968	56.88804	–0.01%
58.967	58.885	–0.01%
60.968	60.88195	–0.01%
62.967	62.87782	–0.01%
64.966	64.87613	–0.01%
69.965	69.86636	–0.01%
74.965	74.85669	–0.02%
79.964	79.85213	–0.01%
84.963	84.84324	–0.01%
89.963	89.83919	–0.01%
94.963	94.835	–0.01%
96.960	96.83171	0.00%
99.960	99.82369	–0.01%
102.962	102.8255	0.00%
105.962	105.8196	–0.01%
107.960	107.8193	0.00%
109.960	109.8188	0.00%
111.959	111.8131	0.00%
114.958	114.8095	0.00%
119.957	119.8032	0.00%
124.957	124.7988	0.00%
126.958	126.7952	0.00%
129.956	128.0000	–1.38%

NOTE: Applied gain multiplication factor is 1.00128.

Table 9. Channel 2: Linearity Performance

$V_{APPLIED}$ (mV)	$V_{CHANNEL2}$ (mV) (WITHOUT GAIN MULTIPLICATION)	$CHANNEL2_{ERROR}$ (AFTER GAIN MULTIPLICATION)
24.972	24.95338	0.06%
29.972	29.93974	0.02%
34.969	34.92714	0.01%
36.969	36.92403	0.01%
38.970	38.91727	0.00%
40.969	40.91727	0.00%
42.969	42.91207	0.00%
44.969	44.90584	–0.01%
46.968	46.91152	0.01%
48.967	48.90452	0.00%
50.970	50.89978	–0.01%
52.970	52.89782	–0.01%
54.967	54.8893	–0.01%
56.968	56.88943	–0.01%
58.967	58.88457	–0.01%
60.968	60.88365	–0.01%
62.967	62.87493	–0.02%
64.966	64.87406	–0.01%
69.965	69.86466	–0.01%
74.965	74.85849	–0.01%
79.964	79.85144	–0.01%
84.963	84.8479	0.00%
89.963	89.83695	–0.01%
94.963	94.83193	–0.01%
96.960	96.82842	0.00%
99.960	99.82069	–0.01%
102.962	102.822	–0.01%
105.962	105.8159	–0.01%
107.960	107.8166	0.00%
109.960	109.8165	0.00%
111.959	111.8078	0.00%
114.958	114.8069	0.00%
119.957	119.8038	0.00%
124.957	124.7929	0.00%
126.958	126.7918	0.00%
129.956	128.0000	–1.38%

NOTE: Applied gain factor is 1.001310.

Table 10. Channel 3: Linearity Performance

$V_{APPLIED}$ (mV)	$V_{CHANNEL3}$ (mV) (WITHOUT GAIN MULTIPLICATION)	$CHANNEL3_{ERROR}$ (AFTER GAIN MULTIPLICATION)
24.972	24.95697	0.07%
29.972	29.94044	0.02%
34.969	34.92873	0.01%
36.969	36.92693	0.01%
38.970	38.92284	0.01%
40.969	40.91598	0.00%
42.969	42.91109	–0.01%
44.969	44.90875	–0.01%
46.968	46.90954	0.00%
48.967	48.9026	0.00%
50.970	50.9006	–0.01%
52.970	52.89588	–0.01%
54.967	54.89344	–0.01%
56.968	56.88652	–0.01%
58.967	58.88598	–0.01%
60.968	60.88221	–0.01%
62.967	62.87755	–0.01%
64.966	64.8734	–0.01%
69.965	69.86158	–0.02%
74.965	74.85734	–0.02%
79.964	79.8507	–0.01%
84.963	84.84557	–0.01%
89.963	89.8371	–0.01%
94.963	94.83109	–0.01%
96.960	96.83072	–0.01%
99.960	99.82227	–0.01%
102.962	102.8224	–0.01%
105.962	105.8192	–0.01%
107.960	107.8165	0.00%
109.960	109.8157	0.00%
111.959	111.8106	0.00%
114.958	114.8075	0.00%
119.957	119.8013	0.00%
124.957	124.7962	0.00%
126.958	126.7951	0.00%
129.956	128.0000	–1.38%

NOTE: Applied gain factor is 1.001284.

Table 11. Channel 4: Linearity Performance

$V_{APPLIED}$ (mV)	$V_{CHANNEL4}$ (mV) (WITHOUT GAIN MULTIPLICATION)	$CHANNEL4_{ERROR}$ (AFTER GAIN MULTIPLICATION)
24.972	24.95606	0.07%
29.972	29.94122	0.03%
34.969	34.92886	0.01%
36.969	36.92489	0.01%
38.970	38.92012	0.00%
40.969	40.91657	0.00%
42.969	42.91369	0.00%
44.969	44.90719	–0.01%
46.968	46.9107	0.01%
48.967	48.90607	0.00%
50.970	50.90158	–0.01%
52.970	52.89598	–0.01%
54.967	54.89154	–0.01%
56.968	56.88658	–0.01%
58.967	58.88463	–0.01%
60.968	60.88013	–0.02%
62.967	62.87574	–0.02%
64.966	64.87512	–0.01%
69.965	69.86325	–0.02%
74.965	74.85668	–0.02%
79.964	79.85253	–0.01%
84.963	84.8452	–0.01%
89.963	89.8364	–0.01%
94.963	94.83339	–0.01%
96.960	96.83004	0.00%
99.960	99.82408	–0.01%
102.962	102.8224	–0.01%
105.962	105.8189	–0.01%
107.960	107.8186	0.00%
109.960	109.814	0.00%
111.959	111.8099	0.00%
114.958	114.8075	0.00%
119.957	119.7999	0.00%
124.957	124.796	0.00%
126.958	126.7941	0.00%
129.956	128.0000	–1.38%

NOTE: Applied gain factor is 1.001292.

When an 130-mV input is applied, for a gain of 16 the output is 2080 mV. The ADC range up to which the linearity performance is guaranteed is 2048 mV. The ADC measurement saturates above 2048 mV.

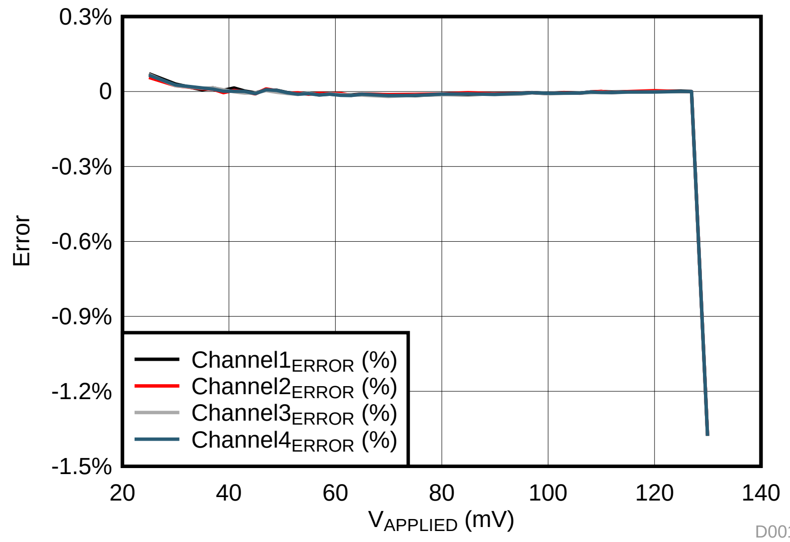

Figure 24. ADC Linearity Performance After Applying Gain Factor

7.2 ADS1248 Characterization in Temperature Measurement Configuration

To test the accuracy of the acquisition circuit alone, a series of high-precision discrete resistors were used as the input to the system. The offset error can be attributed largely due to the offset of the internal PGA and ADC, while the gain error can be attributed to the accuracy of the R_{REF} resistor and gain error of the internal PGA and ADC. The ADC error characterization includes corrections for any mismatch in excitation currents, offset, and gain errors.

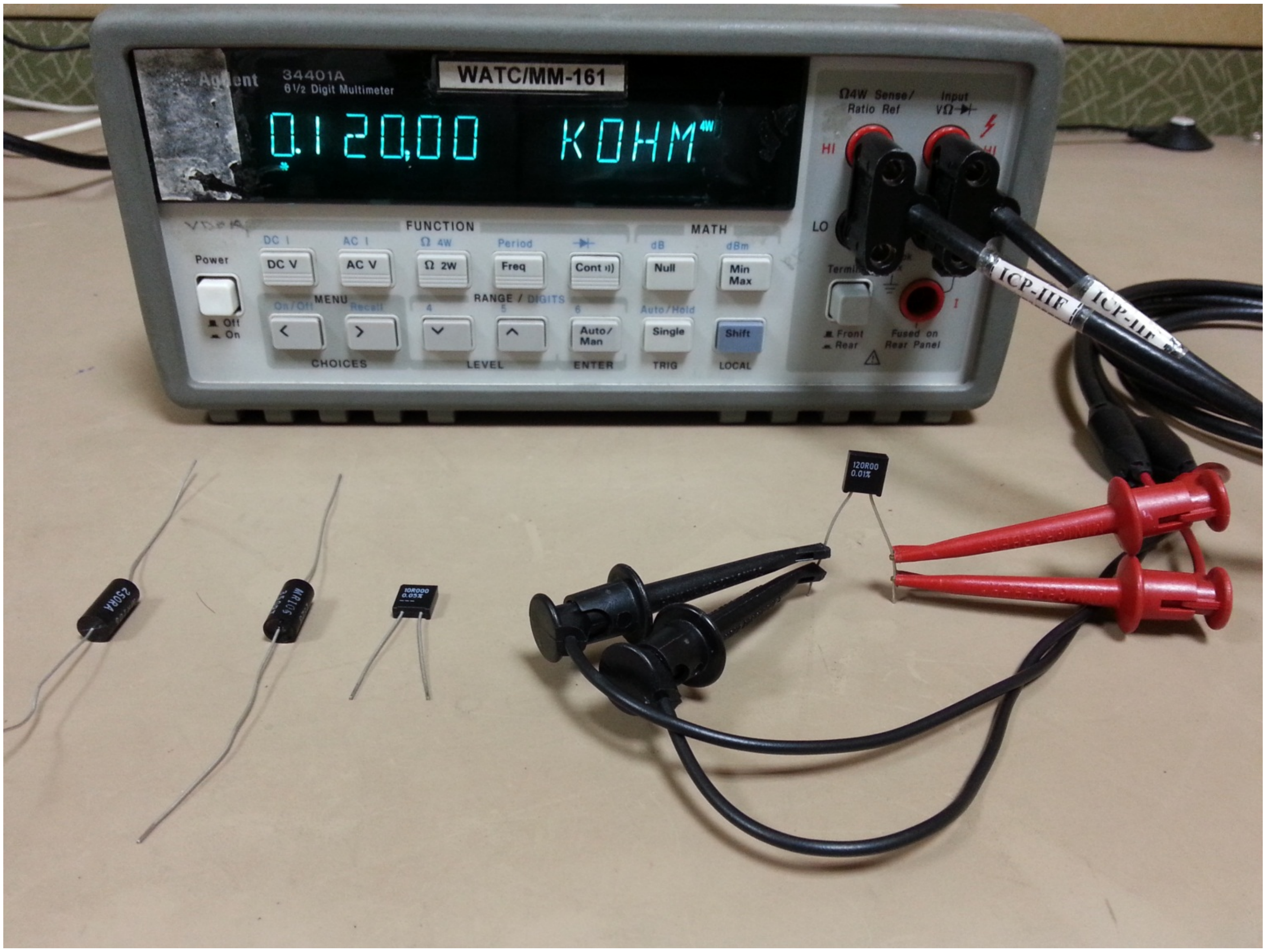

Figure 25. 4-Wire Resistance Measurement Using 6½-Digit Multimeter

The design team followed this procedure for ADD characterization:

1. Chose different resistor values representing the RTD temperature inputs
2. Selected the resistance range equivalent to the temperature range of interest
3. Combined multiple resistors in series and parallel to get the required resistance values
4. Measured the resistance values with a multi-meter using the 4-wire resistance measurement technique
5. Connected the resistors to the RTD input terminals with care to ensure there was no additional resistance being introduced from the contact by tightening the screws
6. Used a GUI to display the measured values

Table 12. RTD1 Measurement

$R_{CONNECTED}$ (Ω)	TEMPERATURE (°C) EQUIVALENT—ACTUAL	RTD1 (Ω)	TEMPERATURE (°C) EQUIVALENT—MEASURED	ERROR (°C)
81.0755	–48.06	81.1769	–47.81	–0.25
89.3629	–27.11	89.48028	–26.81	–0.32
99.9778	–0.06	100.1098	0.28	0.34
119.9989	51.57	120.1415	51.93	0.36
145.8278	119.38	146.0030	119.83	0.45
163.1770	165.74	163.3946	166.29	0.56
179.8721	210.99	180.0964	211.55	0.55

Table 13. RTD2 Measurement

$R_{CONNECTED}$ (Ω)	TEMPERATURE (°C) EQUIVALENT—ACTUAL	RTD2 (Ω)	TEMPERATURE (°C) EQUIVALENT—MEASURED	ERROR (°C)
81.0755	–48.06	81.16632	–47.83	–0.20
89.3629	–27.11	89.46603	–26.84	–0.27
99.9778	–0.06	100.1127	0.29	0.35
119.9989	51.57	120.1418	51.93	0.36
145.8278	119.38	146.0063	119.84	0.46
163.1770	165.74	163.3907	166.28	0.54
179.8721	210.99	180.0973	211.55	0.56

Table 14. RTD3 Measurement

$R_{CONNECTED}$ (Ω)	TEMPERATURE (°C) EQUIVALENT—ACTUAL	RTD3 (Ω)	TEMPERATURE (°C) EQUIVALENT—MEASURED	ERROR (°C)
81.0755	–48.06	81.17819	–47.80	–0.20
89.3629	–27.11	89.47675	–26.82	–0.29
99.9778	–0.06	100.1217	0.31	0.37
119.9989	51.57	120.1531	51.96	0.41
145.8278	119.38	146.0188	119.87	0.51
163.1770	165.74	163.3938	166.29	0.55
179.8721	210.99	180.0995	211.56	0.57

Table 15. RTD4 Measurement

$R_{CONNECTED}$ (Ω)	TEMPERATURE (°C) EQUIVALENT—ACTUAL	RTD4 (Ω)	TEMPERATURE (°C) EQUIVALENT—MEASURED	ERROR (°C)
81.0755	–48.06	81.16966	–47.83	–0.17
89.3629	–27.11	89.46527	–26.85	–0.26
99.9778	–0.06	100.1159	0.30	–0.36
119.9989	51.57	120.1417	51.93	0.36
145.8278	119.38	146.0065	119.84	0.46
163.1770	165.74	163.3884	166.27	0.53
179.8721	210.99	180.094	211.55	0.56

Figure 26 shows error for the four RTS after multiplying the measured mV with gain factor.

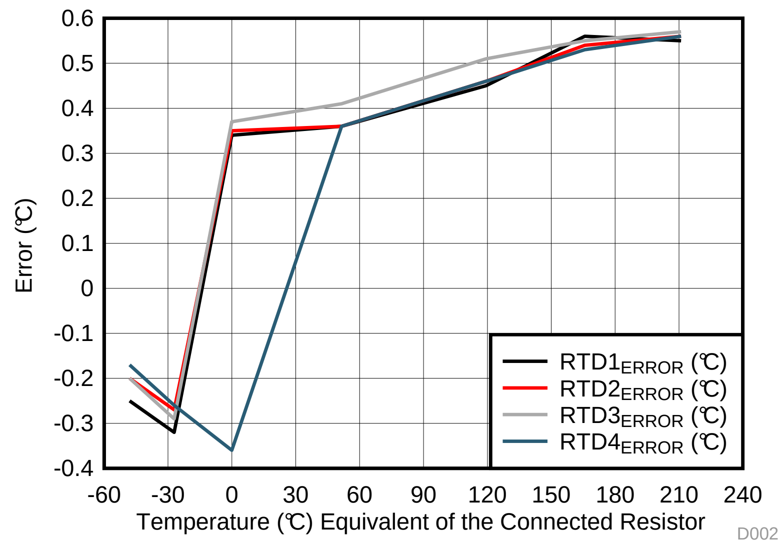

Figure 26. RTD Measurement Accuracy

7.3 Interfacing With Isolated Synchronous Serial Communication Module (TIDA-00300)

This design is a sub-system for sensing multiple RTD channels inside a protection relay or an RTD expansion module. For safety in some of the applications, the RTD inputs are isolated from the measuring system. This design, when interfaced with the Isolated Synchronous Serial Communication Module (TIDA-00300) is configured as an isolated RTD measurement module. TIDA-00300 provides isolation for SPI, I2C, and DC voltage inputs. The interface connectors are simple screw-type connectors enabling easy connection between the two boards.

Isolated RTD functionality is verified with the TIDA-00300 board.

Table 16. Summary

SERIAL NUMBER	TITLE	OBSERVATION
1	Sensing of RTD inputs	ADC measured the inputs as expected
2	ADC, PGA configuration	Measurement follows the programmed gain
3	I2C I/O expander	All I/Os functions were as expected

8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIDA-00110.

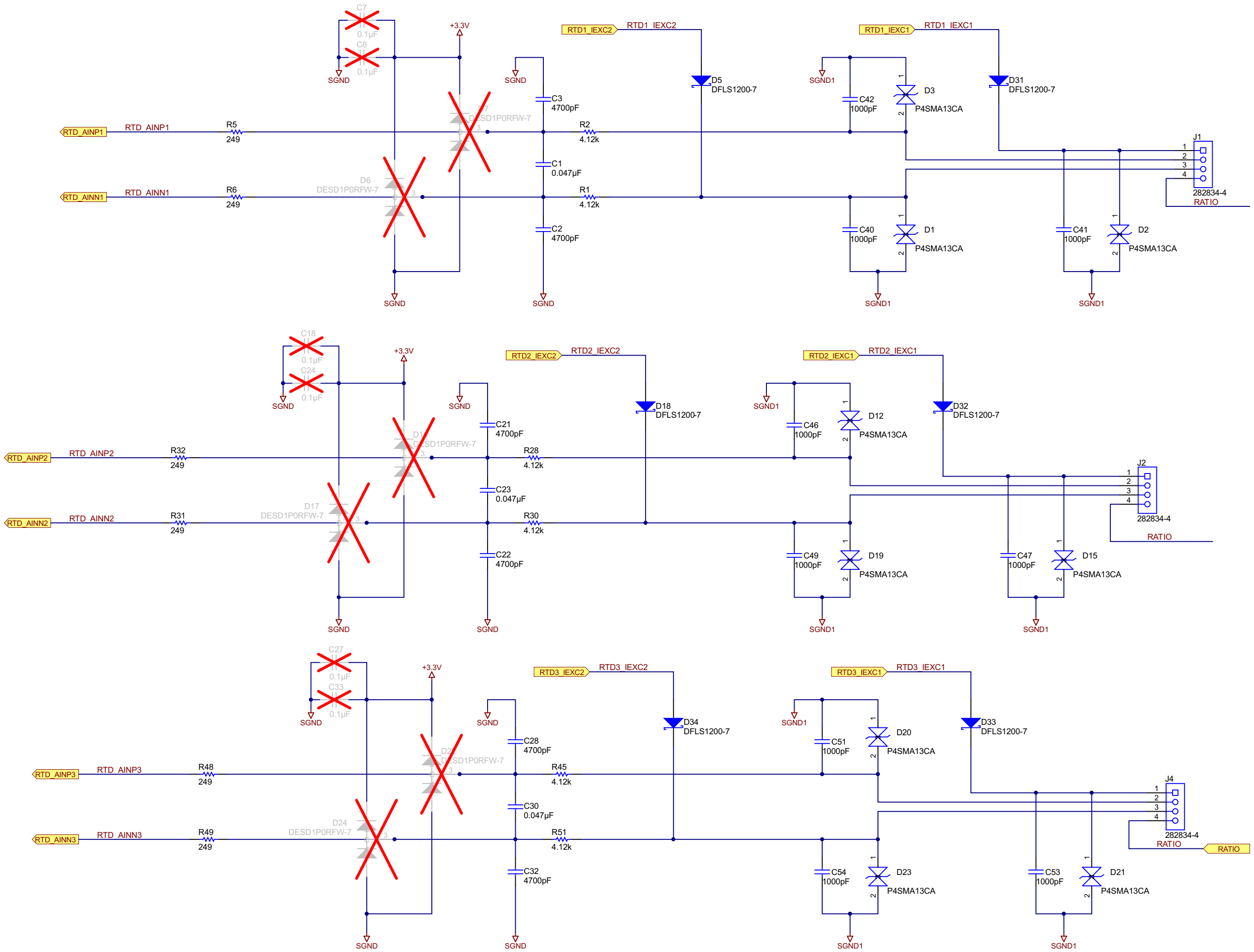

Figure 27. RTD1 to RTD3 Schematic

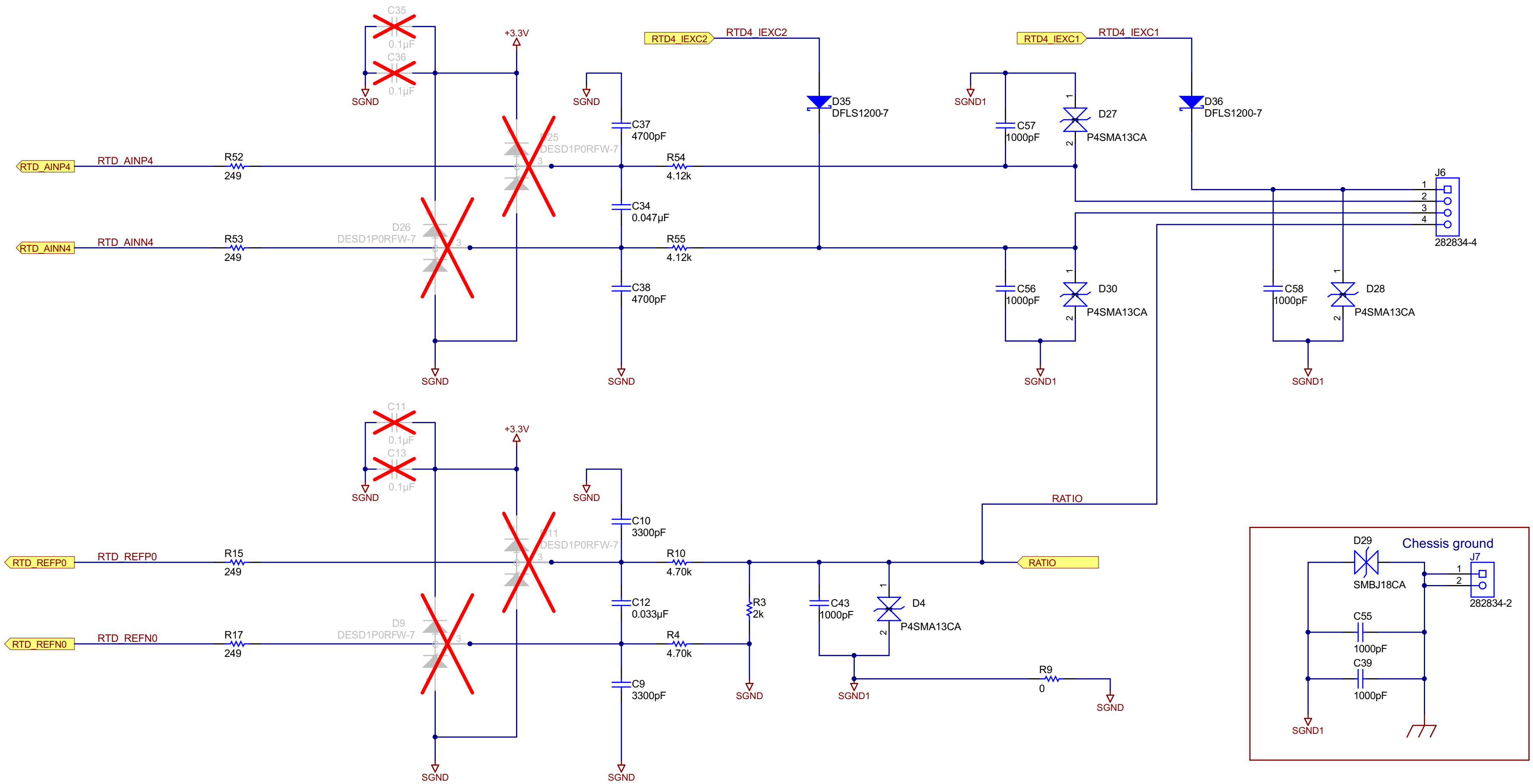

Figure 28. RTD4 and Ratiometric Measurement

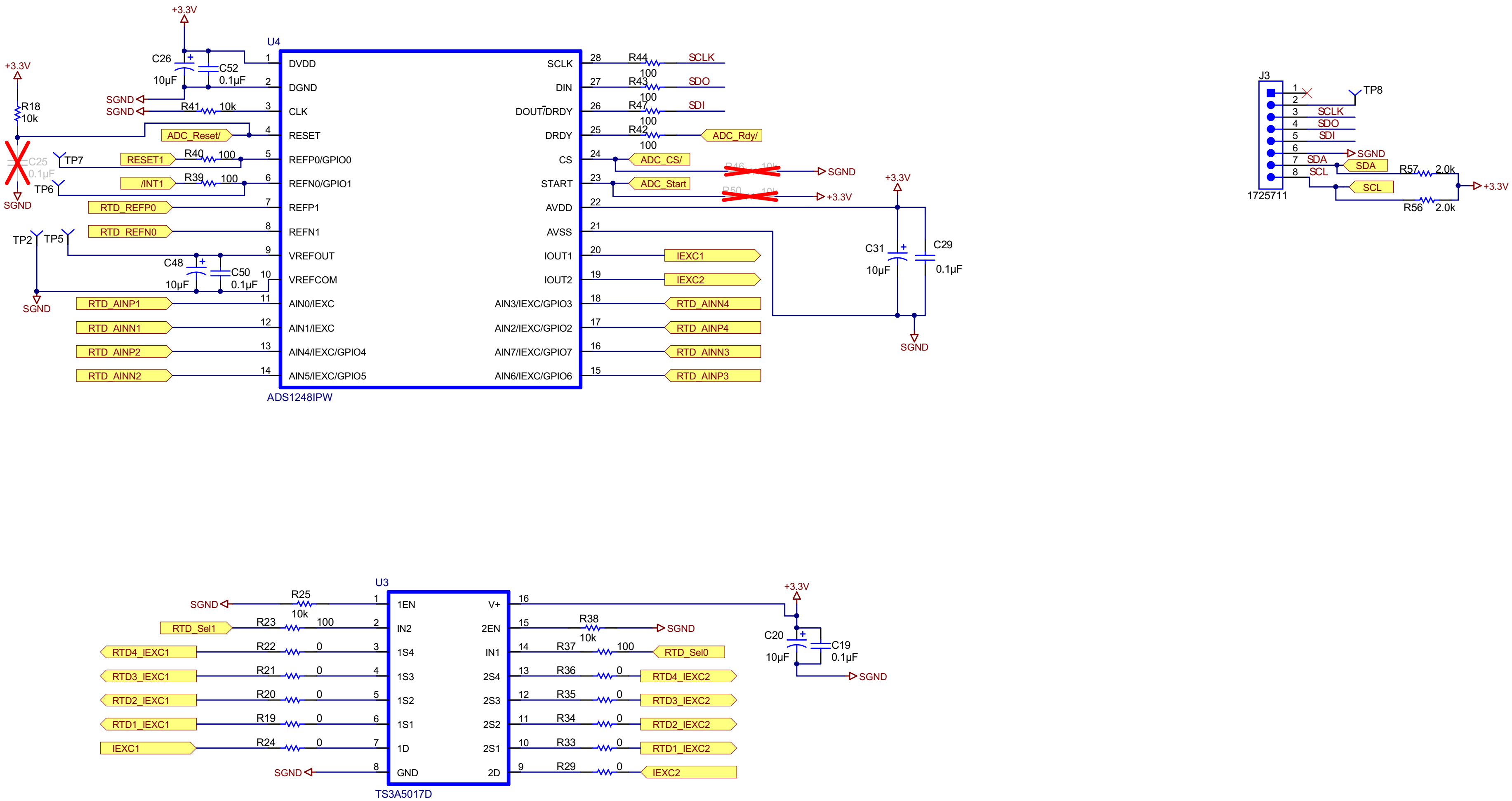

Figure 29. ADS1248 and Analog Switch Circuit

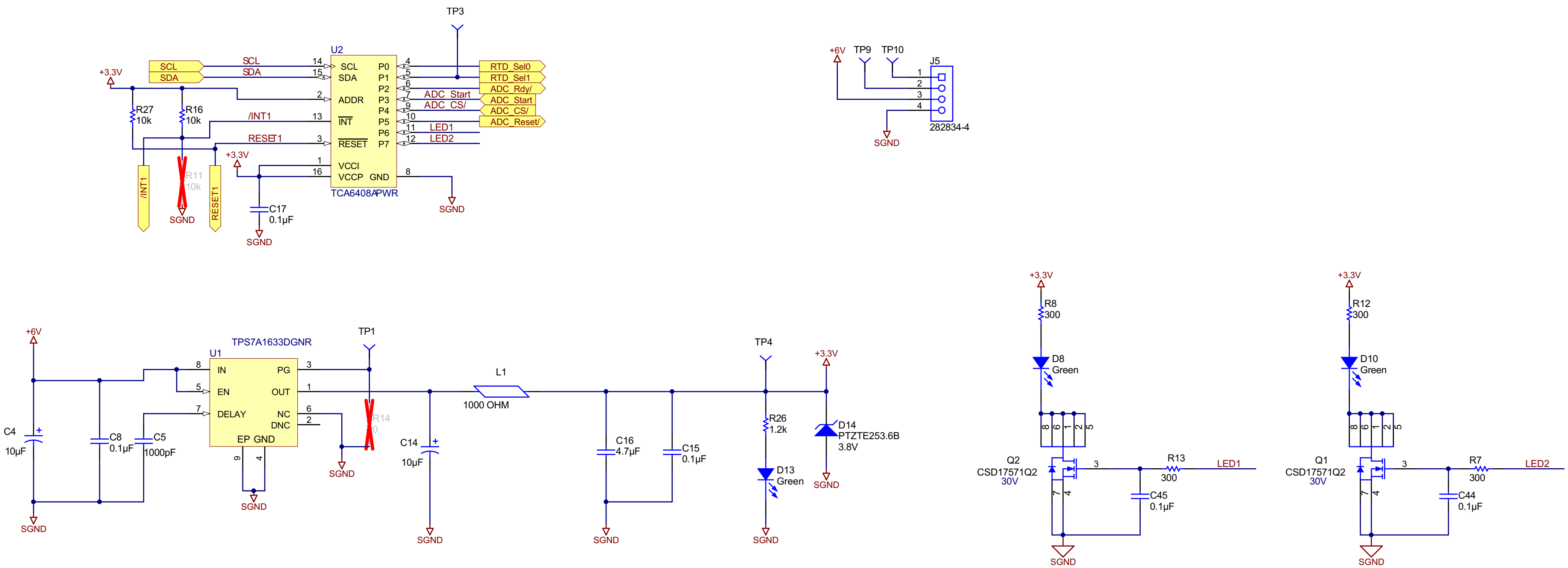

Figure 30. I2C I/O Expander, Power Supply, and LEDs

8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00110.

Table 17. BOM

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PARTNUMBER	PCB FOOTPRINT	DNI
1	!PCB1	Printed Circuit Board	Any	TIDA-00110		
4	C1, C23, C30, C34	CAP, CERM, 0.047 µF, 50 V, ±10%, X7R, 0603	TDK	C1608X7R1H473K	0603	
8	C2, C3, C21, C22, C28, C32, C37, C38	CAP, CERM, 4700 pF, 50 V, ±10%, X8R, 0603	TDK	C1608X8R1H472K	0603	
6	C4, C14, C20, C26, C31, C48	CAP, TA, 10 µF, 16 V, ±10%, 2 Ω, SMD	AVX	F931C106KBA	3528-21	
1	C5	CAP, CERM, 1000 pF, 100 V, ±5%, X7R, 0603	AVX	06031C102JAT2A	0603	
0	C6, C7, C11, C13, C18, C24, C25, C27, C33, C35, C36	CAP, CERM, 0.1 µF, 50 V, ±10%, X7R, 0603	AVX	06035C104KAT2A	0603	DNI
7	C8, C15, C17, C19, C29, C50, C52	CAP, CERM, 0.1 µF, 50 V, ±10%, X7R, 0603	AVX	06035C104KAT2A	0603	
2	C9, C10	CAP, CERM, 3300 pF, 50 V, ±10%, X7R, 0603	Kemet	C0603C332K5RAC TU	0603	
1	C12	CAP, CERM, 0.033 µF, 50 V, ±10%, X7R, 0603	MuRata	GRM188R71H333 KA61D	0603	
1	C16	CAP, CERM, 4.7 µF, 50 V, ±10%, X5R, 0805	TDK	C2012X5R1H475K 125AB	0805	
2	C39, C55	CAP, CERM, 1000 pF, 2 KV 10% X7R 1206	Johanson Dielectrics Inc	202R18W102KV4E	1206	
13	C40, C41, C42, C43, C46, C47, C49, C51, C53, C54, C56, C57, C58	CAP CER, 1000 pF, 100 V, 10% X7R 1206	Yageo	CC1206KRX7R0B B102	1206	
2	C44, C45	CAP, CERM, 0.1 µF, 25 V, ±5%, X7R, 0603	AVX	06033C104JAT2A	0603	
13	D1, D2, D3, D4, D12, D15, D19, D20, D21, D23, D27, D28, D30	TVS Diode 11.1VWM 18.2VC SMD	Littelfuse Inc	P4SMA13CA	SMA	
8	D5, D18, D31, D32, D33, D34, D35, D36	Diode, Schotky, 200 V, 1 A, PowerDI123	Diodes Incorporated	DFLS1200-7	PowerDI123	
0	D6, D7, D9, D11, D16, D17, D22, D24, D25, D26	TVS Diode,70VVVM, 8VC, SOT-323	Diodes Incorporated	DESD1P0RFW-7	SOT-323	DNI
3	D8, D10, D13	LED, SMARTLED, GREEN, 570 NM, 0603	OSRAM Opto Semiconductors Inc	LG L29K-G2J1-24-Z	0603	
1	D14	Diode Zener, 3.8 V, 1 W, PMDS	Rohm Semiconductor	PTZTE253.6B	DO-214AC, SMA	
1	D29	TVS 18-V, 600-W BI-DIR SMB	Littelfuse Inc	SMBJ18CA	SMB	
0	H1, H2, H3, H4	Machine Screw, Round, #4-40 × ¼, Nylon, Philips panhead	B&F Fastener Supply	NY PMS 440 0025 PH	Screw	DNI
5	J1, J2, J4, J5, J6	Receptacle, 100-mil, 4×1 TH	TE Connectivity	282834-4	10.62 × 10 × 6.5 mm	
1	J3	Terminal Block, 8×1, 2.54 mm, TH	Phoenix Contact	1725711	8POS Terminal Block	
1	J7	Terminal Block, 2×1, 2.54mm, TH	TE Connectivity	282834-2	Terminal Block, 2×1, 2.54 mm, TH	

Table 17. BOM (continued)

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PARTNUMBER	PCB FOOTPRINT	DNI
1	L1	Ferrite Chip 1000 Ω, 300 MA, 0603	TDK Corporation	MMZ1608B102C	0603	
0	LBL1	Thermal Transfer Printable Labels, 0.650" W × 0.200" H - 10,000 per roll	Brady	THT-14-423-10	PCB Label 0.650"H × 0.200"W	DNI
2	Q1, Q2	MOSFET, N-CH, 30 V, 22 A, SON 2X2 MM	Texas Instruments	CSD17571Q2	DQK	
8	R1, R2, R28, R30, R45, R51, R54, R55	RES, 4.12 kΩ, 0.1%, 0.1 W, 0603	Susumu Co Ltd	RG1608P-4121-B-T5	0603	
1	R3	RES 2 KΩ, ¼ W, 0.1% 1206	Vishay-Dale	TNPW12062K00BEEA	1206	
2	R4, R10	RES, 4.70 kΩ, 0.1%, 0.1 W, 0603	Susumu Co Ltd	RG1608P-472-B-T5	0603	
10	R5, R6, R15, R17, R31, R32, R48, R49, R52, R53	RES, 249, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603249RFKEA	0603	
4	R7, R8, R12, R13	RES, 300 Ω, 5%, 0.1 W, 0603	Vishay-Dale	CRCW0603300RJNEA	0603	
1	R9	RES, 0 Ω, 5%, 0.125 W, 0805	Yageo America	RC0805JR-070RL	0805	
0	R11, R46, R50	RES, 10 k, 5%, 0.1 W, 0603	Vishay-Dale	CRCW060310K0JNEA	0603	DNI
0	R14	RES, 0, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06030000Z0EA	0603	DNI
6	R16, R18, R25, R27, R38, R41	RES, 10 k, 5%, 0.1 W, 0603	Vishay-Dale	CRCW060310K0JNEA	0603	
10	R19, R20, R21, R22, R24, R29, R33, R34, R35, R36	RES, 0, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06030000Z0EA	0603	
8	R23, R37, R39, R40, R42, R43, R44, R47	RES, 100, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603100RFKEA	0603	
1	R26	RES, 1.2 k, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06031K20JNEAHP	0603	
2	R56, R57	RES, 2.0 k, 5%, 0.1 W, 0603	Yageo America	RC0603JR-072KL	0603	
10	TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10	Test Point 40-mil pad, 20-mil drill	STD	STD		
1	U1	Single Output LDO, 100 mA, Fixed 3.3-V Output, 3- to 60-V Input, with Enable and Power Good, 8-pin MSOP (DGN), –40°C to 125°C, Green (RoHS and no Sb/Br)	Texas Instruments	TPS7A1633DGNR	DGN0008C	
1	U2	Low-Voltage 8-Bit I2C and SMBus I/O Expander, 1.65 to 5.5 V, –40°C to 85°C, 16-pin TSSOP (PW), Green (RoHS and no Sb/Br)	Texas Instruments	TCA6408APWR	PW0016A	
1	U3	IC, Dual, 14 Ω, SP4T Analog Switch	Texas Instruments	TS3A5017D	SO16	
1	U4	IC, 24-Bit A-D Converters for Temperature Sensors	Texas Instruments	ADS1248IPW	TSSOP-28	

8.3 Layer Plots

To download the layer plots, see the design files at TIDA-00110.

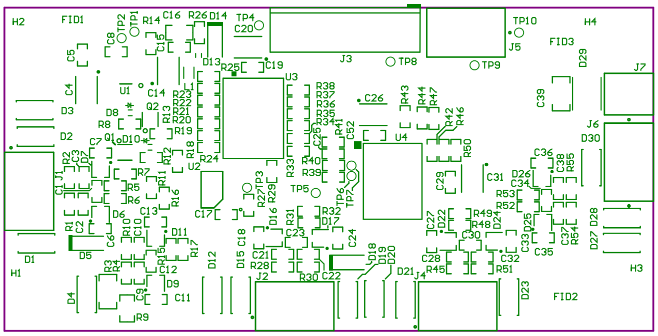

Figure 31. Top Overlay

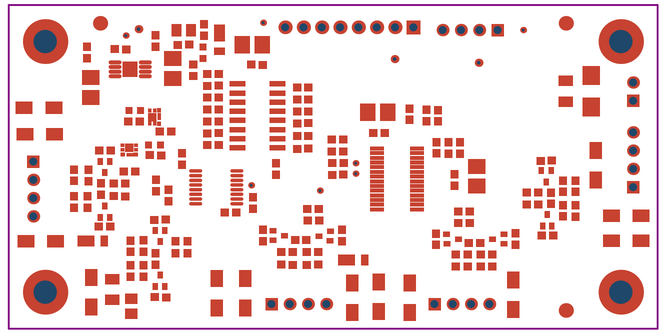

Figure 32. Top Solder

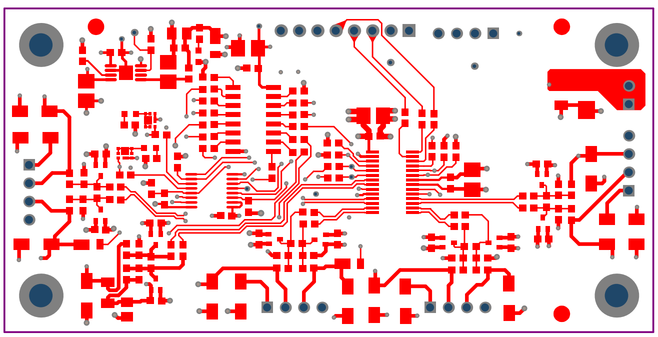

Figure 33. Top Layer

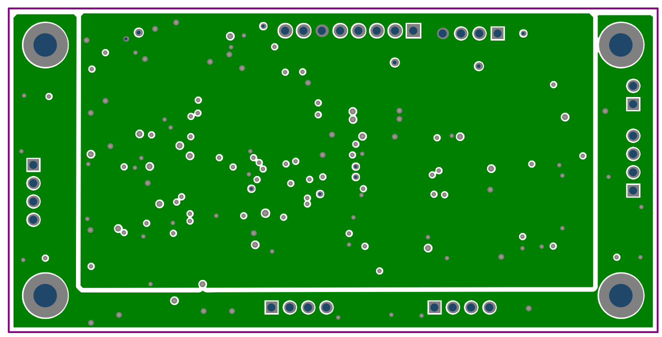

Figure 34. GND Plane

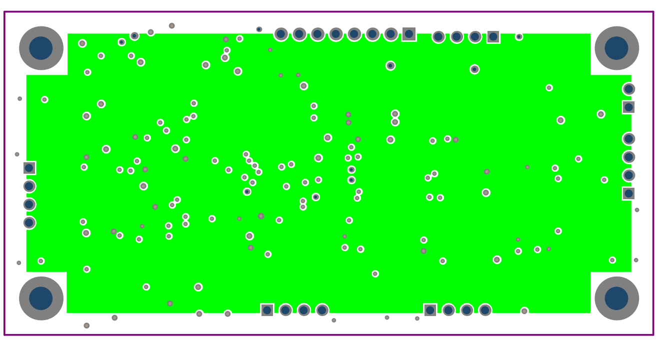

Figure 35. PWR Plane

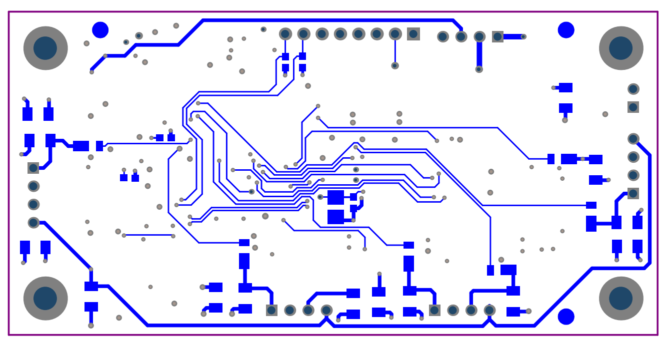

Figure 36. Bottom Layer

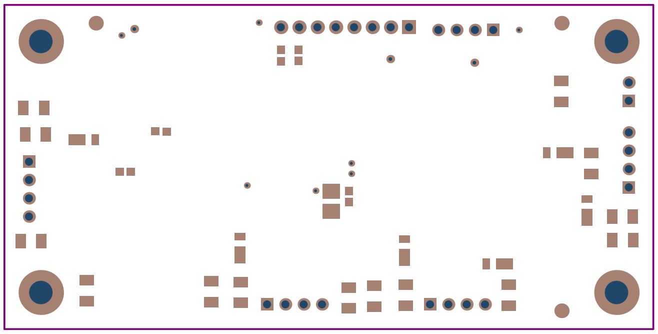

Figure 37. Bottom Solder

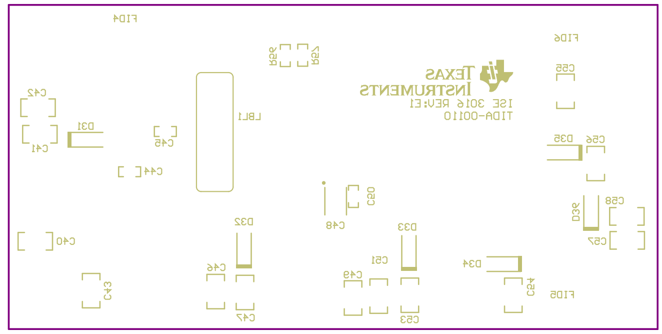

Figure 38. Bottom Overlay

8.4 Altium Project

To download the Altium project files, see the design files at TIDA-00110.

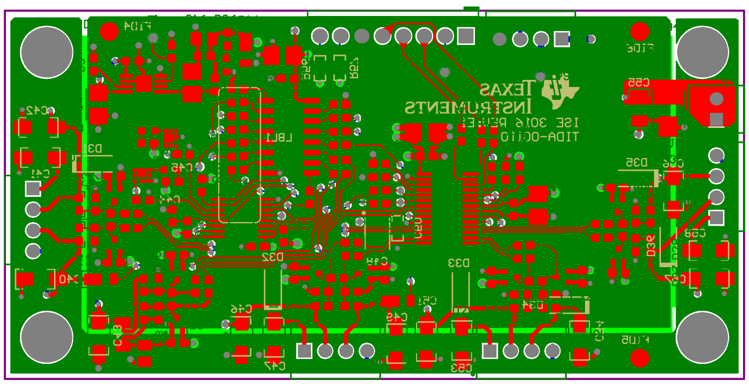

Figure 39. Multilayer Composite Print

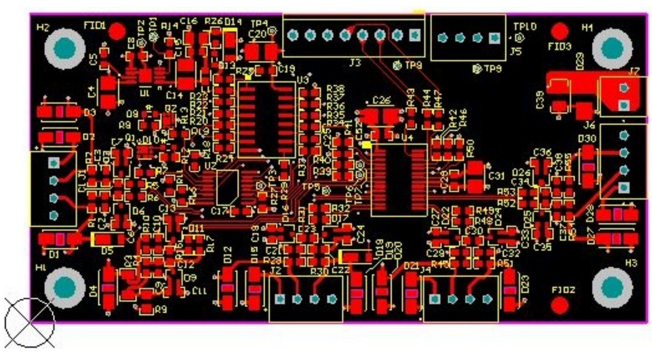

Figure 40. Top Layer

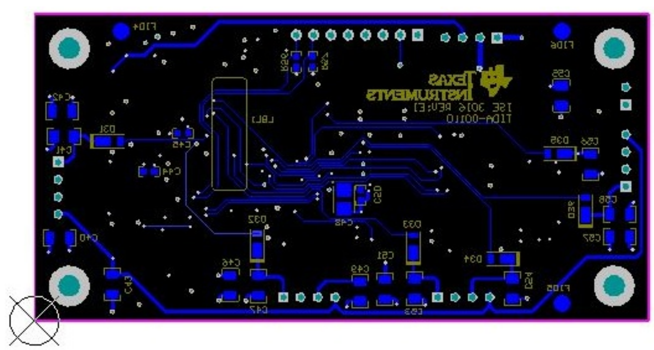

Figure 41. Bottom Layer

8.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00110.

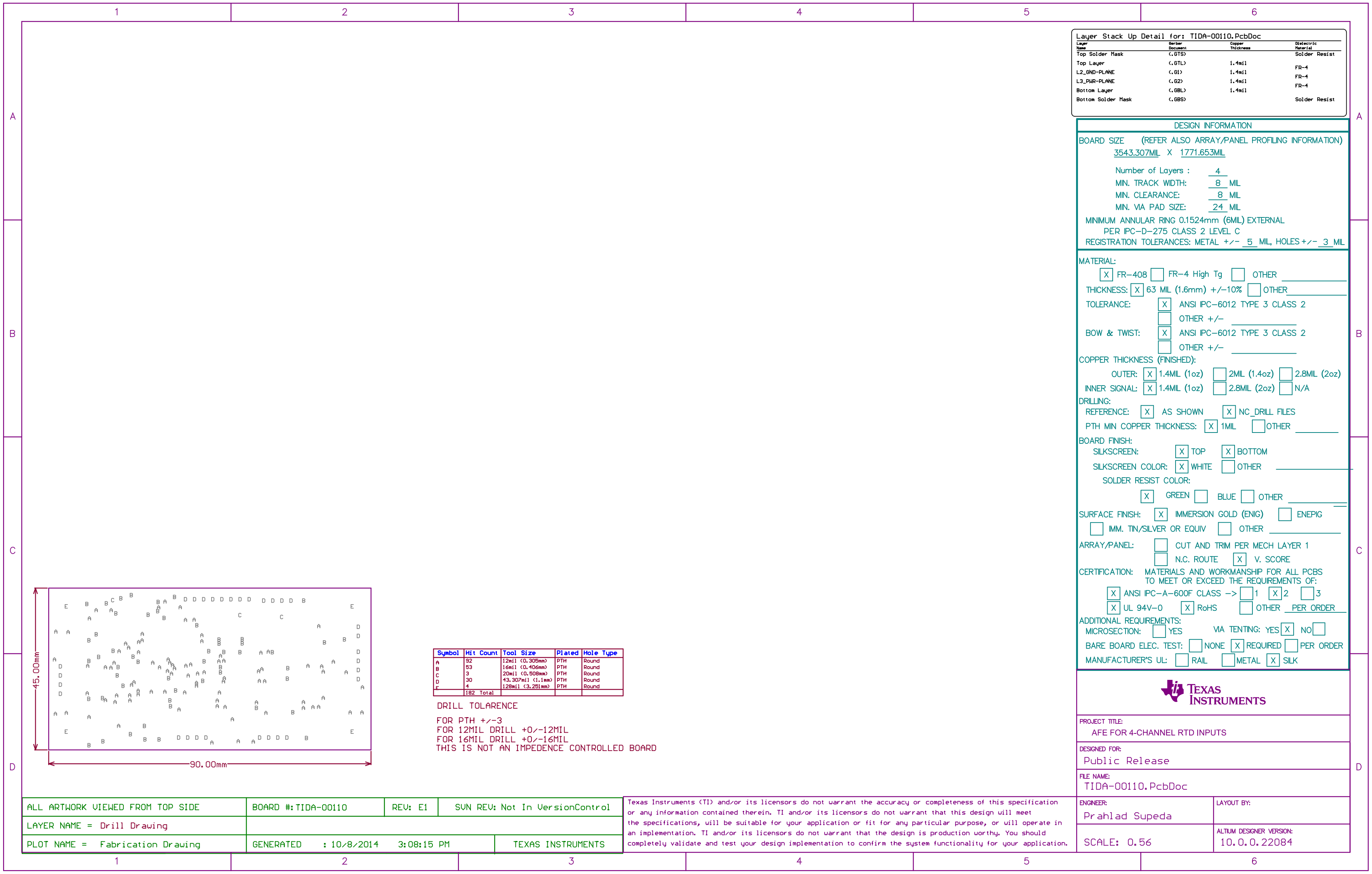

Figure 42. Fabrication Drawing

8.6 Assembly Drawings

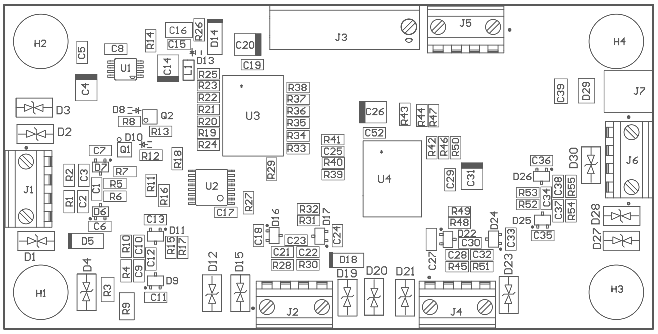

Figure 43. Top Assembly Drawing

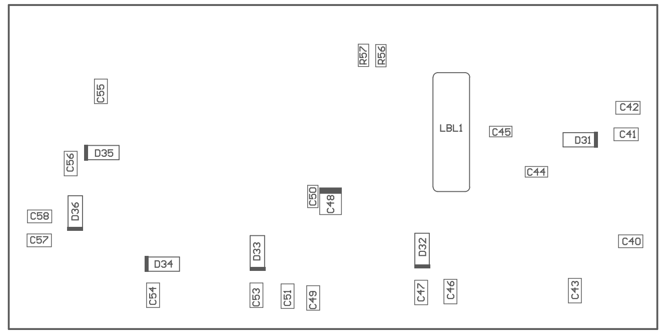

Figure 44. Bottom Assembly Drawing

8.7 Software Files

To download the software files, see the design files at TIDA-00110.

9 References

1. Texas Instruments, *RTD Temperature Transmitter for 2-Wire, 4 to 20-mA Current Loop Systems*, TIDA-00095 Design Guide (TIDU182)
2. Texas Instruments, *RTD Ratiometric Measurements and Filtering Using the ADS1148 and ADS1248 Family of Devices* Application Report (SBAA201)
3. TI Precision, *Hardware-Compensated Ratiometric 3-Wire RTD System, 0°C – 100°C, 0.005°C Error* Design Guide (TIDU045)
4. TI Precision, *3-Wire RTD Measurement System Reference Design, –200°C to 850°C* (SLAU520)
5. Robert Burnham and Nagaraj Ananthapadamanabhan, *Example Temperature Measurement Applications Using the ADS1247 and ADS1248*, Application Report (SBAA180)
6. Collin Wells, *Signal Conditioning and Linearization of RTD Sensors*, 2011 Texas Instruments Technology Day Presentation (TIDU433)
7. Texas Instruments, *Advanced Debugging Using the Enhanced Emulation Module (EEM) With Code Composer Studio Version 6*, Application Report (SLAA393)
8. Texas Instruments, *24-Bit Analog-to-Digital Converters for Temperature Sensors*, ADS1248 Datasheet (SBAS426G)

10 About the Author

PRAHLAD SUPEDA is a systems engineer at Texas Instruments India where he is responsible for developing reference design solutions for Smart Grid within Industrial Systems. Prahlad brings to this role his extensive experience in power electronics, EMC, analog, and mixed signal designs. Prahlad earned his bachelor of instrumentation and control engineering from Nirma University, India. He can be reached at prahlad@ti.com.

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