**Selecting component values
for RTD measurement systems**
TI Precision Labs – ADCs

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TEXAS INSTRUMENTS

Hello, and welcome to the TI Precision Labs module discussing how to select component values for RTD measurement systems. This module steps through an iterative process to help optimize the ADC settings and external components required for a specific set of design goals. A calculation tool is presented at the end of the module that performs this process automatically

Selecting the system settings

1. Choose an RTD configuration and an ADC

2. Identify the largest RTD resistance to be measured, R_RTD (max)

3. Choose a reference resistor, R_REF, that is slightly larger (e.g. 10%) than R_RTD (max)**

4. Calculate the total resistance for each RTD assuming R_RTD (max)

5. Calculate the IDAC compliance voltage and identify the ADC differential reference voltage

6. Select an IDAC value that meets the system requirements

7. Select the maximum gain for each RTD assuming R_RTD (max)

8. Ensure the input signal is within the ADC absolute input voltage limitations

9. Iterate through steps 3-8 if a valid solution is not found

The first step to select the settings for an RTD measurement system is to choose an RTD configuration and an ADC. This includes the reference resistor location and the RTD wiring configuration. Second, identify the largest RTD resistance that needs to be measured by the system, which is called R_RTD max. This single max value is selected from all different RTD types or temperature ranges

Third, select a reference resistor value that is slightly larger than R_RTD max. Typically choosing R_REF to be 10% larger than R_RTD max is sufficient to ensure that the amplified input signal is never larger than the reference voltage, which would result in clipped codes. However, as noted in the upper right corner, these requirements are slightly different for systems that only measure 3-wire RTD using two IDACs and a low-side R_REF

Fourth, calculate the total system resistance for each RTD assuming R_RTD max. The total system resistance includes all resistance in the path between the IDAC output and ground. Fifth, calculate the IDAC compliance voltage and identify the ADC differential reference voltage.

These specifications are provided in the ADC datasheet

Sixth, choose an IDAC value that meets the system requirements thus far, including the compliance voltage and the reference voltage. Seventh, select a gain value for each RTD, assuming the maximum resistance to be measured is R_RTD max. Eighth, ensure that the input signal is within the ADC absolute input voltage limitations. These limits are set by the integrated gain amplifier to maintain linear operation

Finally, iteration might be necessary if the previous steps did not yield a valid result. Loop back through steps 3 through 8 if a viable solution is not found. Since this is a fairly complex process, the rest of this presentation steps through a design example to make the goal of each step more clear

Selecting an RTD configuration & an ADC

This example uses a 4-wire RTD and a low-side R_REF

Same process used for all configurations, however additional considerations can be required for:
- 3-wire RTD with 2x IDACs
- High-side R_REF

This example will use the *ADS124S08*, a 24-bit, 13-channel** delta-sigma ADC with integrated:
- IDACs
- PGA
- Differential VREF inputs

4-wire, low-side RTD measurement system

ADS124S08

**Not all channels shown
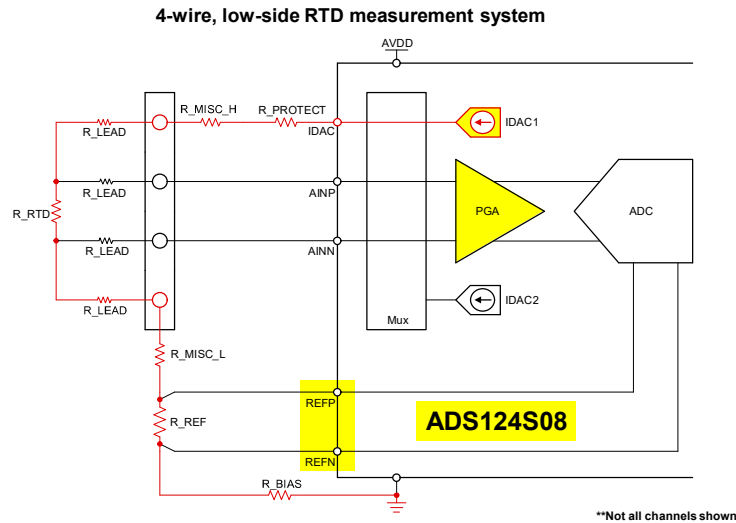
Our example system measures a 4-wire RTD using a low-side R_REF. A generic version of this system is shown on the right side of this slide. The IDAC current highlighted in red flows from the IDAC, through the RTD, through R_REF, and then out to ground. The PGA amplifies this voltage, which can be measured by the ADC

Note that though this same process is used for all different RTD configurations, additional considerations are necessary for 3-wire RTD systems or when a high-side R_REF is used. Some of these considerations will be discussed in this module. Refer to the Precision Labs module on challenges with 3-wire RTD systems for additional information

Finally, this example uses the ADS124S08, a 24-bit, 13 channel delta-sigma ADC. This ADC is selected because it includes dual, matched IDACs for RTD biasing, a low-noise PGA to amplify small signals, and differential reference voltage inputs to implement a ratiometric reference. As a result of the high integration of this device, the ADS124S08 is commonly-used in RTD measurement systems

Let's move on to the next step

Identifying RTD_MAX and selecting R_REF

4-wire, low-side RTD measurement system

RTD measurement parameters

RTD	Temperature Range		Resistance Range (Ω)	
	Min	Max	Min	Max
Ni1000	-60°C	+180°C	695.2	2232.2
Cu50	-100°C	+260°C	25.6	95.58
Pt100	-100°C	+450°C	60.3	264.2
Pt1000	-100°C	+450°C	602.6	2641.8

R_RTD (max)

Choose a reference resistor, R_REF, that is slightly larger (e.g. 10%) than R_RTD (max)

For this example, choose R_REF = 2870 Ω

Next we need to select the maximum RTD resistance to be measured, as well as R_REF. To do so, some example RTD measurement parameters are given in the table on the left. On the right is a simplified version of the system we are trying to design

The table on the left reveals that the maximum RTD resistance that needs to be measured is 2641.8 ohms, which is the equivalent resistance of a Pt1000 RTD at 450 degrees Celsius

The next step is to choose an R_REF resistance that is slightly larger compared to the value of R_RTD max

For this example, let's choose R_REF to be 2870 ohms, which is a standard resistance value approximately 8.5% larger than R_RTD max. Since R_REF needs to be high accuracy and low drift, selecting a standard resistance value makes this component easier to find and therefore more cost effective

Now let's calculate the total circuit resistance

Total circuit resistance seen by the IDAC

$$R\_TOTAL = R\_PROTECT + R\_MISC\_H + 2 * R\_LEAD$$
$$+ R\_RTD + R\_MISC\_L + R\_REF + R\_BIAS$$

4-wire, low-side RTD measurement system

No R_MISC_H = 0 Ω

1000 Ω
IDAC
IDAC1
AVDD

1 Ω

1 Ω — AINP

R_RTD

1 Ω — AINN

1 Ω

No R_MISC_L = 0 Ω

2870 Ω — REFP

REFN

No R_BIAS = 0 Ω

System resistance values

RTD	Description	Resistance (Ω)
R_PROTECT	Limits current into IDAC pin	1000
R_MISC_H	Miscellaneous e.g. mux R_{ON}	0
R_LEAD	RTD lead resistance	1
R_MISC_L	Miscellaneous e.g. mux R_{ON}	0
R_BIAS	Helps shift signal common-mode	0

$$R\_TOTAL = 1000 + 0\ \Omega + 2 * 1\ \Omega + R\_RTD\ (max) + 0\ \Omega$$
$$+ 2870\ \Omega + 0\ \Omega$$

$$R\_TOTAL = 3872\ \Omega + R\_RTD\ (max)$$
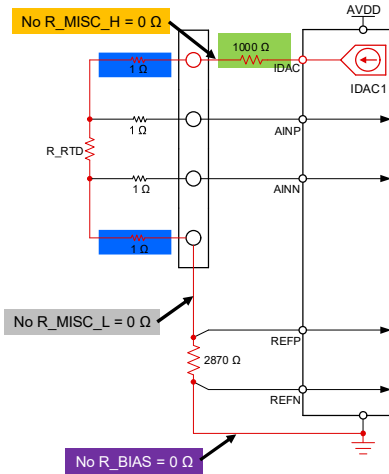
As discussed in a previous Precision Labs module introducing RTD measurement circuits, total circuit resistance is defined as the combined resistance between the IDAC output and ground.

In the example 4-wire RTD system on the right, the IDAC current follows the red path as shown. While we only really care about the IDAC current establishing a voltage across the RTD and R_REF, it is clear that the IDAC current can pass through several additional resistances. Therefore, R_TOTAL is the sum of all of these resistances, as per the equation on the top left. The table on the left includes a description of several resistance values that can be present in the system. Let's assign values to each so we can calculate total circuit resistance

In this example, we'll choose R_PROTECT to be 1000 ohms because this component acts as a current limiting resistor to help protect the ADC in case of an overvoltage event. Some miscellaneous resistance could exist before or after the RTD, from a mux for example, but we will set these to 0 to keep the analysis simple. Then, R_LEAD is selected to be 1 ohm. Finally, we don't need R_BIAS because we are using a low-side

R_REF, so we can set this to 0 as well

We can now simplify the circuit on the right and assign the selected values to each resistance, as shown. Note that any resistance set to 0 ohms in the table on the left is removed from the image on the right. Ultimately, R_TOTAL for the example circuit is equal to 3872 ohms plus the maximum RTD resistance

Next, let's consider IDAC compliance and the reference voltage range

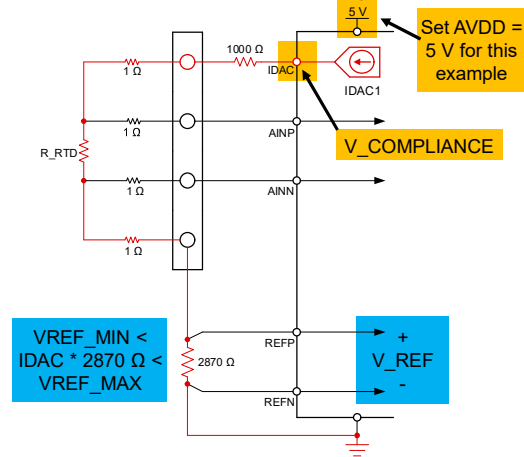## IDAC compliance & VREF range

ADS124S08 IDAC Settings and Compliance Voltage

Parameter	Condition	MIN	TYP	MAX	Unit
Current settings			10, 50, 100, 250, 500, 750, 1000, 1500, 2000		µA
Compliance voltage	10 µA to 750 µA, 0.1% deviation	AVSS		AVDD – 0.4	V
	1 mA to 2 mA, 0.1% deviation	AVSS		AVDD – 0.6	

ADS124S08 Voltage Reference Inputs

Parameter	Condition	MIN	TYP	MAX	Unit
V_{REF}	$V_{REF} = V_{REFP} - V_{REFN}$	0.5		AVDD – AVSS	V

Each parameter helps set a range of valid IDAC values

4-wire, low-side RTD measurement system

Set AVDD = 5 V for this example

V_COMPLIANCE

VREF_MIN < IDAC * 2870 Ω < VREF_MAX

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Two other parameters we need to consider before completing the design are IDAC compliance and the voltage reference range. On the left are specifications from the ADS124S08 datasheet. The top table shows the IDAC compliance voltage parameters highlighted in orange. The bottom table shows the voltage reference input range, which is highlighted in blue. Let's focus on IDAC compliance for now

The IDAC compliance voltage is the voltage seen at the IDAC output pin. This is highlighted in orange in the figure on the right. The table on the left shows that the IDAC compliance voltage on the ADS124S08 varies depending on the IDAC setting and is relative to the analog supply voltage, AVDD. To enable the maximum possible compliance voltage, let's set AVDD equal to 5 V as shown

Next, the ADS124S08 voltage reference input table specifies a minimum differential V_REF of 0.5 V and a maximum of AVDD – AVSS. Since we are using a unipolar supply in this example, the maximum VREF voltage is just AVDD, or 5 V. Therefore, the IDAC current multiplied by the R_REF resistance must be between the V_REF minimum and maximum,

as shown

These parameters are important because they each help set limits on the range of possible IDAC values

Selecting the IDAC value

$$V\_REF = R\_REF * IDAC$$
$$(R\_REF = 2870\ \Omega)$$

IDAC (µA)	V_REF (V)
10	0.03
50	0.14
100	0.29
250	0.72
500	1.44
750	2.15
1000	2.87
1500	4.31
2000	5.74

$$0.5\ V < V\_REF < 5\ V$$

$$V\_COMPLIANCE = R\_TOTAL * IDAC$$
$$[R\_TOTAL = 3872\ \Omega + R\_RTD\ (max)]$$

IDAC (µA)	Max**	Compliance Voltage (V) Ni1000	Cu50	Pt100	Pt1000
250	4.6	1.53	0.99	1.03	1.63
500	4.6	3.05	1.98	2.07	3.26
750	4.6	4.58	2.98	3.10	4.89
1000	4.4	6.10	3.97	4.14	6.51
1500	4.4	9.16	5.95	6.20	9.77

V_COMPLIANCE (RTD) < V_COMPLIANCE (Max)

Choose the largest IDAC value = largest input signal to the ADC:

- Ni100 → 500 µA
- Cu50 → 1000 µA
- Pt100 → 1000 µA
- Pt1000 → 500 µA

To help narrow down the possible IDAC values to use in our system, let's first consider how the limits on the reference voltage impact this choice. On the left are all of the possible IDAC output currents provided by the ADS124S08. The equation for the V_REF voltage is given above the table, while the limits from the previous slide are shown below the table. Given that R_REF is equal to 2870 ohms, we can calculate the resulting V_REF values as shown in the table on the left. The IDAC settings highlighted in orange all produce a V_REF voltage that satisfies the inequality. Next, let's see if we can further reduce the available IDAC settings by considering the IDAC compliance voltage

The table on the right shows our new, limited set of possible IDAC settings and the corresponding maximum compliance voltage for each. Note that the compliance voltage was calculated using the ADS124S08 compliance voltage equation shown on the previous slide. Given that R_TOTAL is equal to 3872 ohms plus R_RTD max, we can calculate the resulting compliance voltages values as shown. Note that the maximum RTD resistance for each RTD was provided earlier in this presentation. The compliance voltages highlighted in blue all satisfy the inequality as shown, and are therefore valid IDAC settings we can select for our
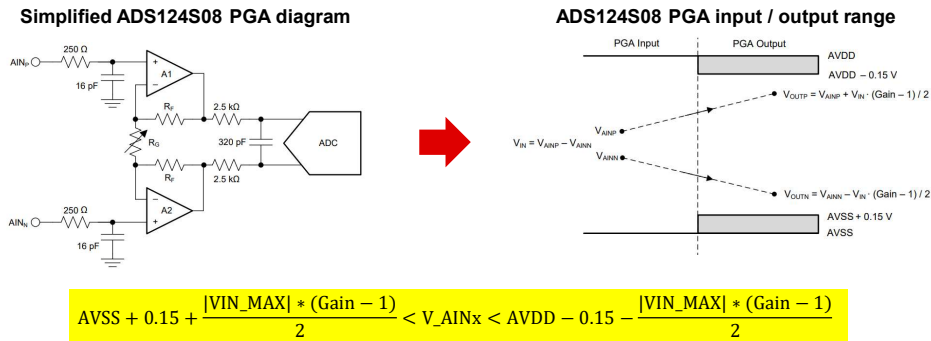
system.

In this case, select the largest possible IDAC value because this produces the largest input signal to the ADC. However, it is not necessary to choose the largest value, this is just a recommendation. In some cases a smaller IDAC value might need to be used if power consumption is absolutely critical or if self-heating is a concern. Refer to the Precision Labs module on error sources for more information about RTD self-heating

Since each RTD can be supplied with a different IDAC current, the list highlighted in yellow summarizes the IDAC settings for each RTD.

Next, let's move on to selecting the gain values for each RTD as well as verifying the input voltage requirements

Gain and absolute input range

Simplified ADS124S08 PGA diagram

ADS124S08 PGA input / output range

$$AVSS + 0.15 + \frac{|VIN\_MAX| * (Gain - 1)}{2} < V\_AINx < AVDD - 0.15 - \frac{|VIN\_MAX| * (Gain - 1)}{2}$$

RTD measurement parameters

RTD type	IDAC (µA)	R_RTD (Ω, max)	R_REF (Ω)	Max gain	VIN_MAX (V)
Ni1000	500	2232.2		1	1.116
Cu50	1000	95.58	2870	16	0.096
Pt100	1000	264.2		8	0.264
Pt1000	500	2641.8		1	1.321

Choose the largest available gain value < (R_REF / R_RTD)

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Shown here on the left is a simplified diagram of the PGA integrated into the ADS124S08. We use this PGA to produce low noise measurements by gaining up the low level RTD voltages. As a result, we also need to consider the voltage limitations of the amplifier input and output stages. A diagram of these limitations for the ADS124S08 is shown on the right. Note that the gray areas in the output stage represent the nonlinear region of operation, and should be avoided

To ensure that the absolute voltage limitations are met, the ADS124S08 datasheet provides an inequality that depends on the supply voltage, the gain, and the maximum PGA input voltage as shown. This inequality can restrict the possible gain values we can select for each RTD. The table on the bottom shows the relevant parameters for the four different RTDs in our example system. In order to determine if our selections satisfy the inequality, we first need to select gain values

To begin, let's start by choosing the maximum gain allowable as determined by the note on the right. We know that the input signal multiplied by the gain must be less than the reference voltage, so
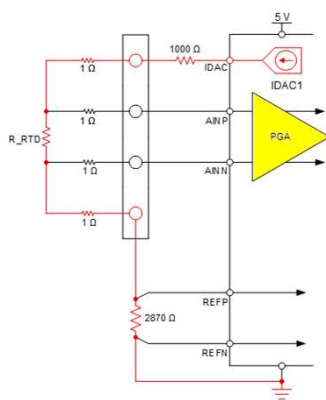
dividing R_REF by the RTD resistance gives us the maximum possible gain. We then need to cross reference these calculated values with the gain settings available in the ADS124S08. The resulting gain settings for our system are highlighted in yellow in the table

Then, we can calculate the maximum input voltage by multiplying the IDAC current and the maximum RTD resistance. This is also highlighted in yellow in the table
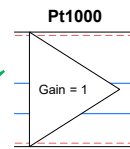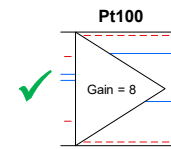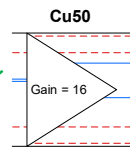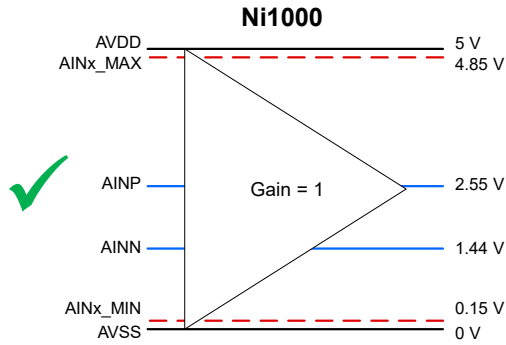
The next slide applies these RTD measurement parameters to the inequality to verify that they do not violate the ADS124S08 operating specifications

Verifying absolute input voltage

4-wire, low-side RTD measurement system

Ni1000

AVDD	5 V
AINx_MAX	4.85 V
AINP	2.55 V
AINN	1.44 V
AINx_MIN	0.15 V
AVSS	0 V

Gain = 1

$$V\_AINP = IDAC * (R\_RTD + R\_LEAD + R\_REF)$$
$$V\_AINN = IDAC * (R\_LEAD + R\_REF)$$

Cu50 — Gain = 16 ✓
Pt100 — Gain = 8 ✓
Pt1000 — Gain = 1 ✓

5 V, 1000 Ω, IDAC, IDAC1, AINP, AINN, R_RTD, PGA, REFP, REFN, 2870 Ω, 1 Ω

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The image on the left shows the 4-wire RTD measurement system we have been analyzing throughout this example. We have selected all of the necessary system parameters, and the only remaining step is to verify that the voltage across each RTD does not violate the absolute input voltage limitations of the PGA. Let's start by analyzing the Ni1000 RTD

Recall that the Ni1000 RTD uses a gain of 1 as shown, and we are using a unipolar 5V supply. Inputting this information into the equation on the previous slide yields a maximum absolute input voltage of 4.85 V and a minimum absolute input voltage of 0.15 V. In other words, both the voltage on A_IN_P and the voltage on A_IN_N in the diagram on the left must be between the voltages highlighted in yellow

Next, we can calculate the actual voltages seen by the A_IN_P and A_IN_N pins using the equations on the bottom left of this slide. For the Ni1000 RTD, A_IN_P is 2.55 V and A_IN_N is 1.44 V. Since both of these voltages are within A_IN_MIN and A_IN_MAX, this combination of settings for the Ni1000 RTD does not violate the absolute input voltage

limitations on the ADS124S08

We can perform a similar analysis for the remaining three RTD types, which is shown on the bottom right of the slide. Note that all of our selected parameters meet the absolute input voltage requirements, which means our design is complete

Summary of results

RTD measurement parameters

RTD	Temperature Range		Resistance Range (Ω)	
	Min	Max	Min	Max
Ni1000	-60°C	+180°C	695.2	2232.2
Cu50	-100°C	+260°C	25.6	95.58
Pt100	-100°C	+450°C	60.3	264.2
Pt1000	-100°C	+450°C	602.6	2641.8

System settings[**]

RTD	IDAC (µA)	Gain	Compliance (V)	AINN (V)	AINP (V)
Ni1000	1000	1	3.05	1.44	2.55
Cu50	500	16	3.97	2.87	2.97
Pt100	500	8	4.14	2.87	3.14
Pt1000	1000	1	3.26	1.44	2.76

4-wire, low-side RTD measurement system
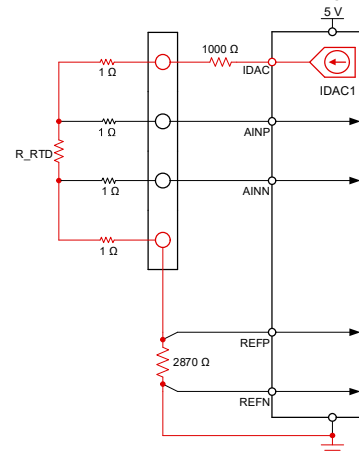
[**]Can require further iterations if all conditions are not satisfied

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The table on the top left lists the RTD measurement parameters used in this example, while the image on the right is the 4-wire RTD measurement system we are analyzing.

After stepping through the general design process for an RTD application, we selected the system settings shown in the table on the bottom left. At each step in the process we verified that our selected settings met the requirements of the ADS124S08, and therefore each combination is valid for all RTDs.

If for some reason the settings were invalid at any point in the design process, further iterations may have been necessary to identify an acceptable solution

While this may have been a complicated process, TI has developed a design tool to help

The RTD configuration calculator is an online tool that automates the process presented in this Precision Labs module

This online tool allows the user to choose up to 5 different RTD types in any of the 8 common RTD configurations. Then, an algorithm can be run that optimizes the system settings for all designs. Or, it is possible to manually enter information to see if certain combinations of settings are valid.

The RTD configuration tool also calculates first order error approximations using the information presented in a previous Precision Labs module on error sources in RTD measurement systems

An image of the RTD configuration tool is shown on the right, and the tool itself can be accessed via the link on the screen

Thanks for your time! Please try the quiz.

That concludes this video. Thank you for watching. Please try the quiz to check your understanding of this video's content.

Quiz: Selecting RTD system component values

1. Why is the total circuit resistance important?
   a. It is used to identify the maximum RTD resistance, RTD_MAX
   b. It is needed to determine if the IDAC compliance voltage is met
   c. This is not an important parameter for system component selection

2. Why is it necessary to verify the absolute input voltage on each ADC input?
   a. This ensures we are not violating the IDAC compliance voltage
   b. This ensures we are able to measure Pt100 and Pt1000
   c. This ensures we are only operating in the PGA's linear region

Question 1. Why is the total circuit resistance important?

The correct answer is B, total circuit resistance is needed to determine if the IDAC compliance voltage is met

Question 2. Why is it necessary to verify the absolute input voltage on each ADC input pin?

The correct answer is C, this ensures we are only operating in the PGA's linear region

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