Challenges with 3-wire RTD systems

TI Precision Labs – ADCs

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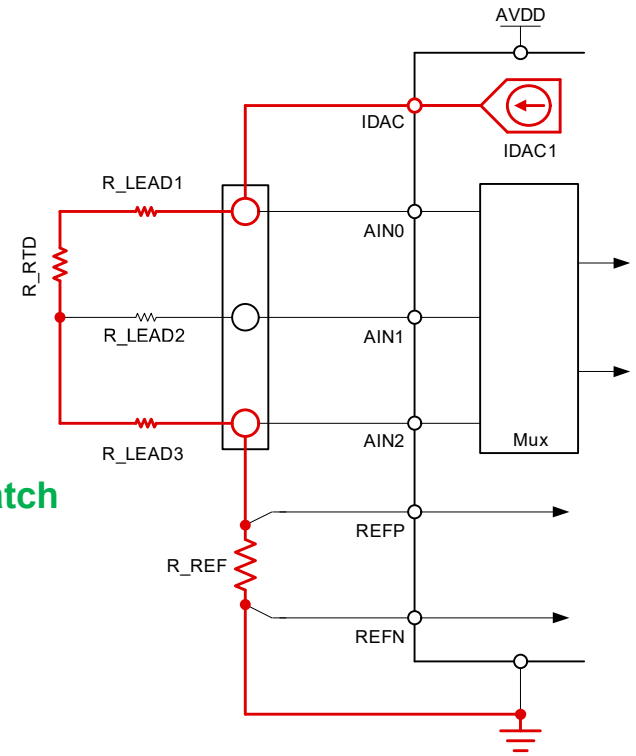
**Low-side R_REF shown; high-side R_REF is possible

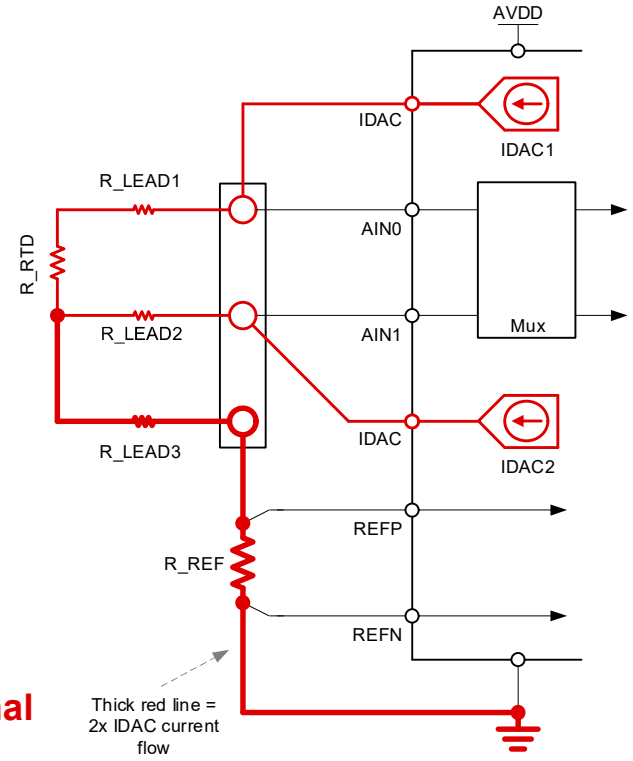
1x IDAC versus 2x IDACs for 3-wire RTDs

3-wire RTD using 1x IDAC**



- ✓ No IDAC mismatch errors
- × Requires 2x measurements

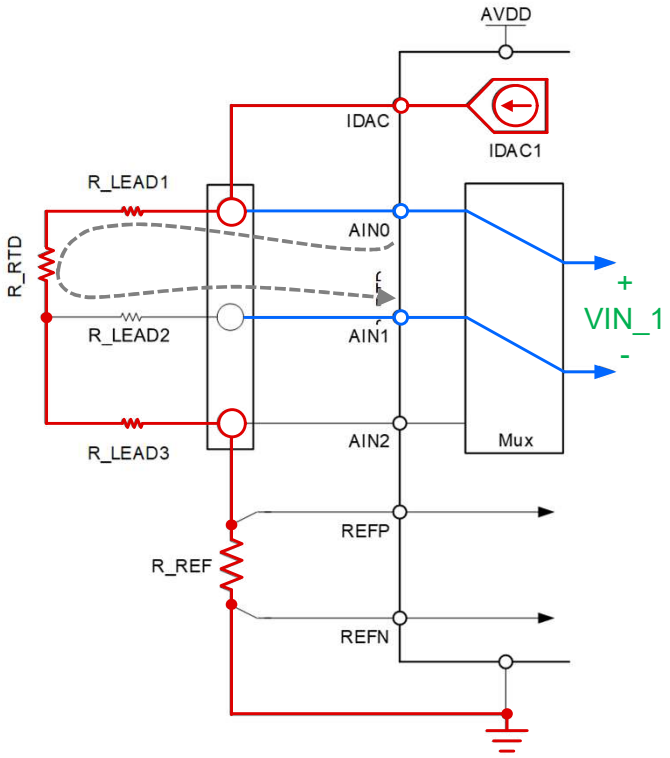
3-wire RTD using 2x IDACs**



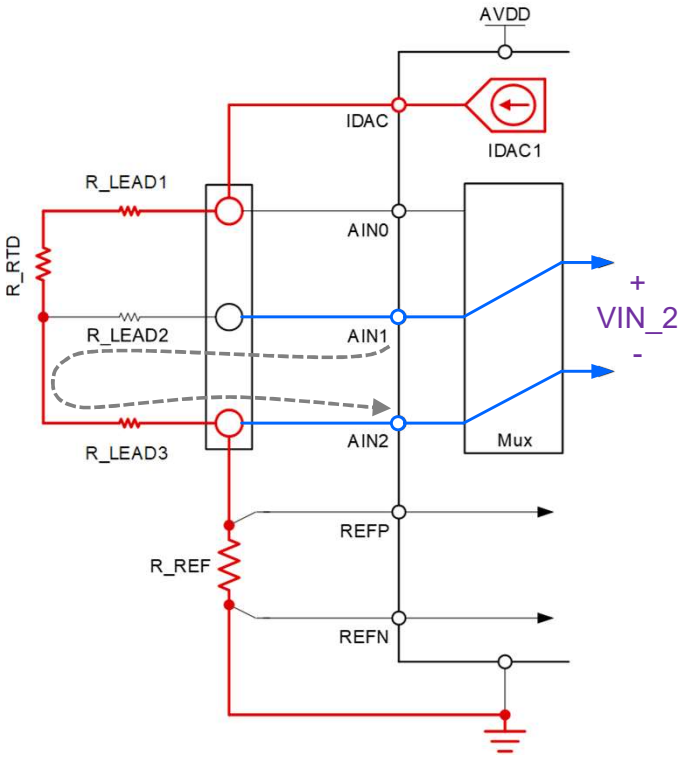
- ✓ Automatic lead resistance cancellation
- × IDAC mismatch causes additional error

Two measurements using 3-wire RTD and 1x IDAC

Circuit for measurement #1



Circuit for measurement #2



$$VIN\_1 = AIN0 - AIN1$$

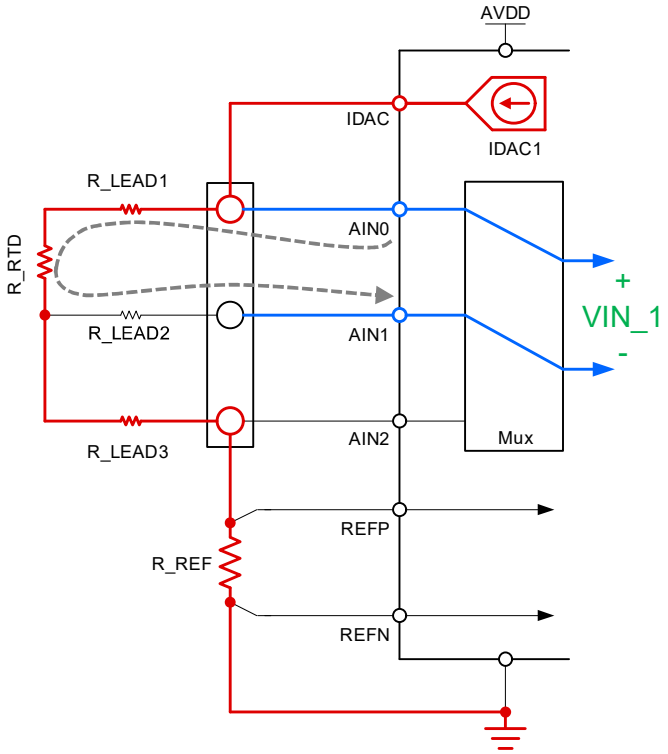
$$VIN\_1 = V\_LEAD1 + V\_RTD$$

$$VIN\_2 = AIN1 - AIN2$$

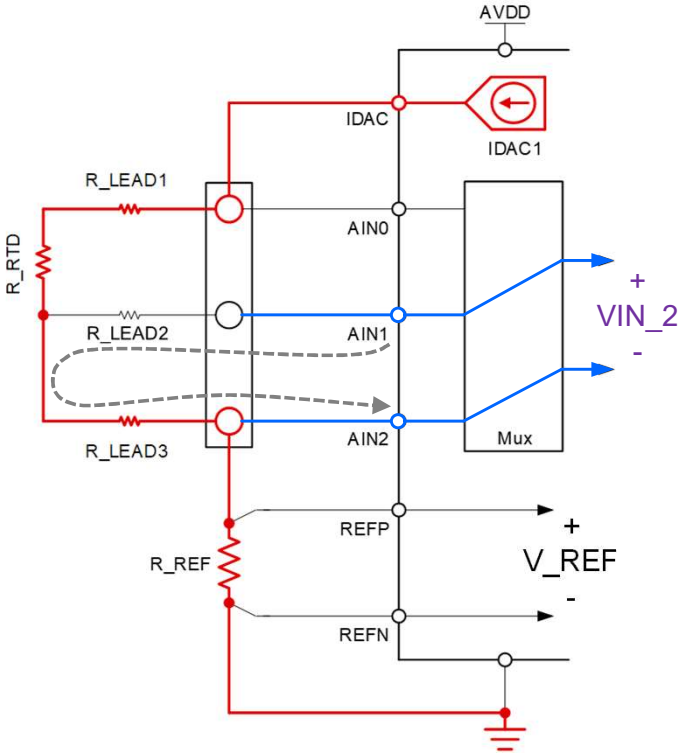
$$VIN\_2 = V\_LEAD3$$

ADC output code for a 3-wire RTD using 1x IDACs

Circuit for measurement #1



Circuit for measurement #2



$$VIN\_1 = V\_LEAD1 + V\_RTD$$

$$VIN\_2 = V\_LEAD3$$

$$V\_REF = IDAC1 * R\_REF$$

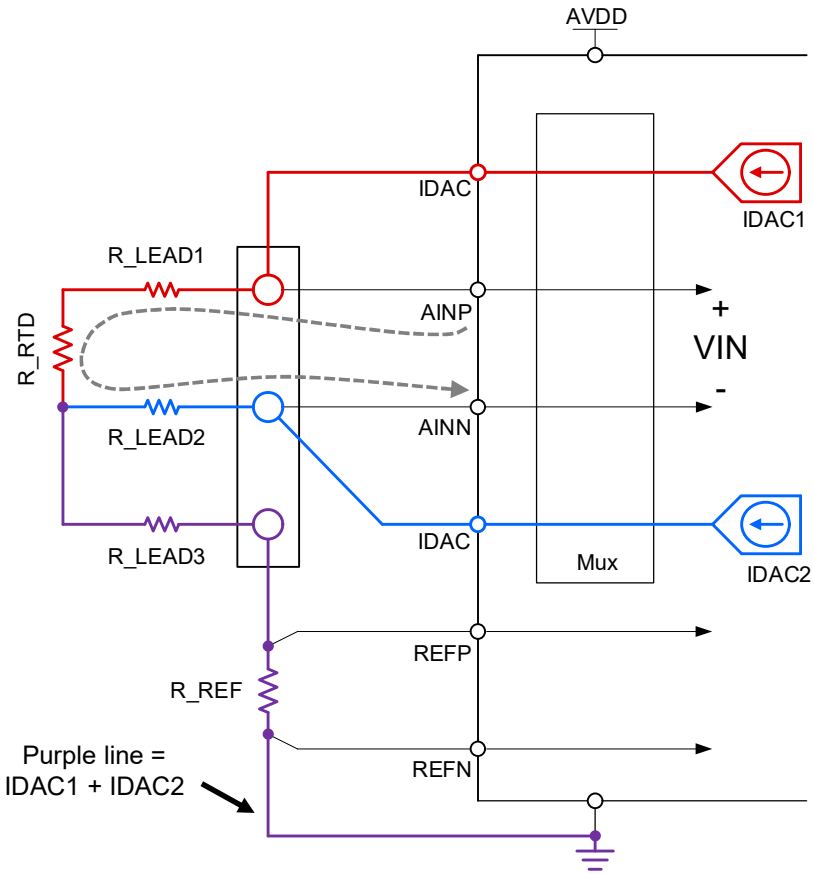
$$\text{ADC code} = \frac{VIN\_1}{V\_REF} - \frac{VIN\_2}{V\_REF}$$

$$= \frac{IDAC1 * R\_RTD}{IDAC1 * R\_REF} + \frac{IDAC1 * R\_LEAD1}{IDAC1 * R\_REF} - \frac{IDAC1 * R\_LEAD3}{IDAC1 * R\_REF}$$

$$\text{ADC code} = \frac{R\_RTD^{**}}{R\_REF}$$

**If R_LEAD1 = R_LEAD3

Measuring VIN (3-wire RTD, 2x IDACs, LS R_REF)



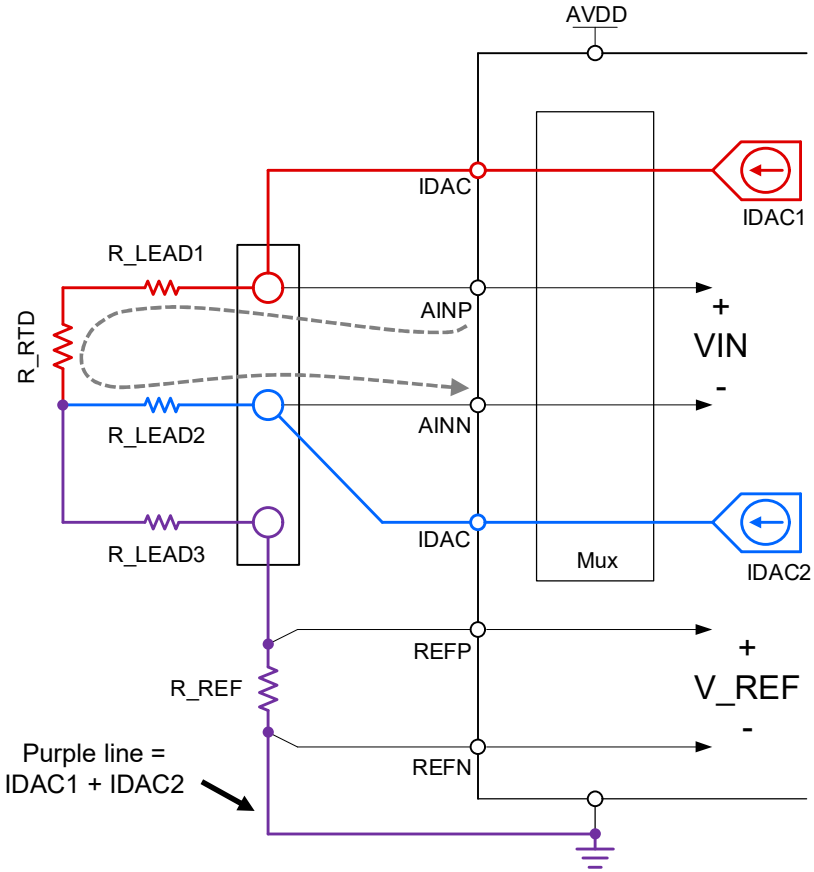
$$\underline{VIN = AINP - AINN}$$

$$VIN = V\_LEAD1 + V\_RTD - V\_LEAD2$$

- $V\_LEAD1 = IDAC1 * R\_LEAD1$
- $V\_RTD = IDAC1 * R\_RTD$
- $V\_LEAD2 = IDAC2 * R\_LEAD2$

$$VIN = IDAC1 * (R\_RTD + R\_LEAD1) - IDAC2 * R\_LEAD2$$

ADC output code (3-wire RTD, 2x IDACs, LS R_REF)



$$VIN = IDAC1 * (R\_RTD + R\_LEAD1) - IDAC2 * R\_LEAD2$$

$$V\_REF = (IDAC1 + IDAC2) * R\_REF$$

$$ADC\ code = \frac{VIN}{V\_REF}$$

Assume IDAC1 = IDAC2

$$= \frac{IDAC1 * (R\_RTD + R\_LEAD1) - IDAC2 * R\_LEAD2}{(IDAC1 + IDAC2) * R\_REF}$$

$$= \frac{R\_RTD + R\_LEAD1 - R\_LEAD2}{2 * R\_REF}$$

Assume R_LEAD1 = R_LEAD2

$$= \frac{R\_RTD}{2 * R\_REF}$$

Understanding IDAC specifications

Compliance voltage ensures both IDACs can maintain constant current

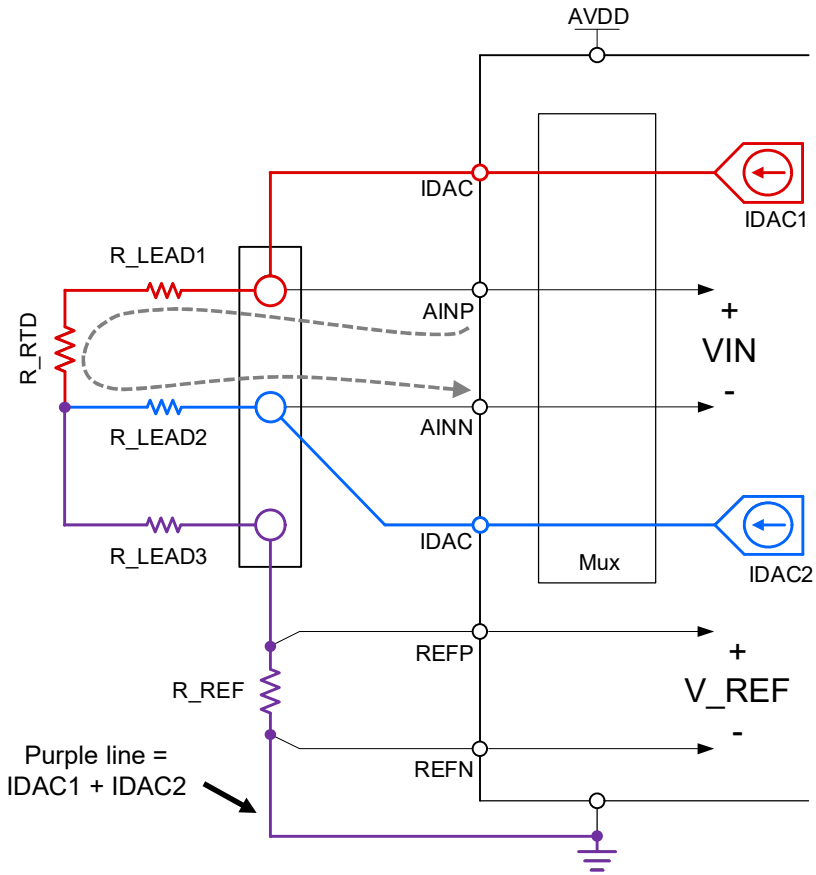
Ratiometric measurements allow relaxed absolute IDAC specifications

Matching specifications are most critical for 3-wire RTD systems using 2x IDACs

ADS124S08 IDAC parameters

Parameter	Condition	MIN	TYP	MAX	Unit
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	
Accuracy (each IDAC)	T_A = 25°C, 10 µA to 100 µA	-5%	0.7%	5%	
	T_A = 25°C, 250 µA to 2 mA	-3%	0.5%	3%	
Temperature drift (each IDAC)	10 µA to 750 µA		20	120	ppm/°C
	1 mA to 2 mA		10	80	
Current mismatch between IDACs	T_A = 25°C, 10 µA to 100 µA		0.15%	0.8%	
	T_A = 25°C, 250 µA to 750 µA		0.10%	0.6%	
	T_A = 25°C, 1 mA to 2 mA		0.07%	0.4%	
Temperature drift matching between IDACs	10 µA to 100 µA		3	25	ppm/°C
	250 µA to 2 mA		2	15	

How IDAC mismatch errors affect 3-wire RTDs



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	T_A = 25°C, 1 mA to 2 mA		0.07%	0.4%	

$$\text{ADC code} = \frac{\text{VIN}}{\text{V\_REF}}$$

$$= \frac{\text{IDAC1} * (\text{R\_RTD} + \text{R\_LEAD}) - \text{IDAC2} * \text{R\_LEAD}}{(\text{IDAC1} + \text{IDAC2}) * \text{R\_REF}}$$

IDAC mismatch error (E_{IM})

$$E_{IM} = 1 - \frac{\text{IDAC1}}{\text{IDAC2}}$$

- IDAC1 = 500 µA
- IDAC2 = 503 µA
- Mismatch error = 0.006 (0.6%)

$$\text{IDAC1} = \text{IDAC2} * (1 - E_{IM})$$

How IDAC mismatch affects 3-wire RTDs (LS R_REF)

IDAC mismatch error (E_{IM})

$$E_{IM} = 1 - \frac{IDAC1}{IDAC2}$$

$$IDAC1 = IDAC2 * (1 - E_{IM})$$

$$ADC\ code = \frac{IDAC1 * (R\_RTD + R\_LEAD) - IDAC2 * R\_LEAD}{(IDAC1 + IDAC2) * R\_REF}$$

$$ADC\ code = \frac{IDAC2 * (1 - E_{IM}) * (R\_RTD + R\_LEAD) - IDAC2 * R\_LEAD}{[IDAC2 * (1 - E_{IM}) + IDAC2] * R\_REF}$$

$$ADC\ code = \frac{(R\_RTD + R\_LEAD - R\_LEAD * E_{IM} - R\_RTD * E_{IM}) - R\_LEAD}{[(1 - E_{IM}) + 1] * R\_REF}$$

$$ADC\ code = \frac{R\_RTD * (1 - E_{IM}) - R\_LEAD * E_{IM}}{(2 - E_{IM}) * R\_REF}$$

$$ADC\ code = \frac{R\_RTD * (1 - E_{IM})}{R\_REF * (2 - E_{IM})} - \frac{R\_LEAD * E_{IM}}{R\_REF * (2 - E_{IM})}$$

How much ADC error does IDAC mismatch contribute?

Calculating ADC error due to E_{IM} (LS R_REF)

General form of the error equation

$$\text{ADC error} = \left(\frac{\text{ADC code}_{\text{Mismatch}} - \text{ADC code}_{\text{Ideal}}}{\text{ADC code}_{\text{Ideal}}}\right) * 100\%$$

Apply system-specific expressions

$$\text{ADC error} = \left(\frac{\left[\frac{\text{R\_RTD} * (1 - \text{E}_{\text{IM}})}{\text{R\_REF} * (2 - \text{E}_{\text{IM}})} - \frac{\text{R\_LEAD} * \text{E}_{\text{IM}}}{\text{R\_REF} * (2 - \text{E}_{\text{IM}})}\right] - \left[\frac{\text{R\_RTD}}{2 * \text{R\_REF}}\right]}{\frac{\text{R\_RTD}}{2 * \text{R\_REF}}}\right) * 100\%$$

Divide out R_REF

$$\text{ADC error} = \left(\frac{\left[\frac{\text{R\_RTD} * (1 - \text{E}_{\text{IM}})}{2 - \text{E}_{\text{IM}}} - \frac{\text{R\_LEAD} * \text{E}_{\text{IM}}}{2 - \text{E}_{\text{IM}}}\right] - \left[\frac{\text{R\_RTD}}{2}\right]}{\frac{\text{R\_RTD}}{2}}\right) * 100\%$$

Multiply top and bottom by $\frac{2}{\text{R\_RTD}}$ and simplify

$$\text{ADC error} = \left(\frac{2 * (1 - \text{E}_{\text{IM}})}{2 - \text{E}_{\text{IM}}} - \frac{2 * \text{R\_LEAD} * \text{E}_{\text{IM}}}{\text{R\_RTD} * (2 - \text{E}_{\text{IM}})} - 1\right) * 100\%$$

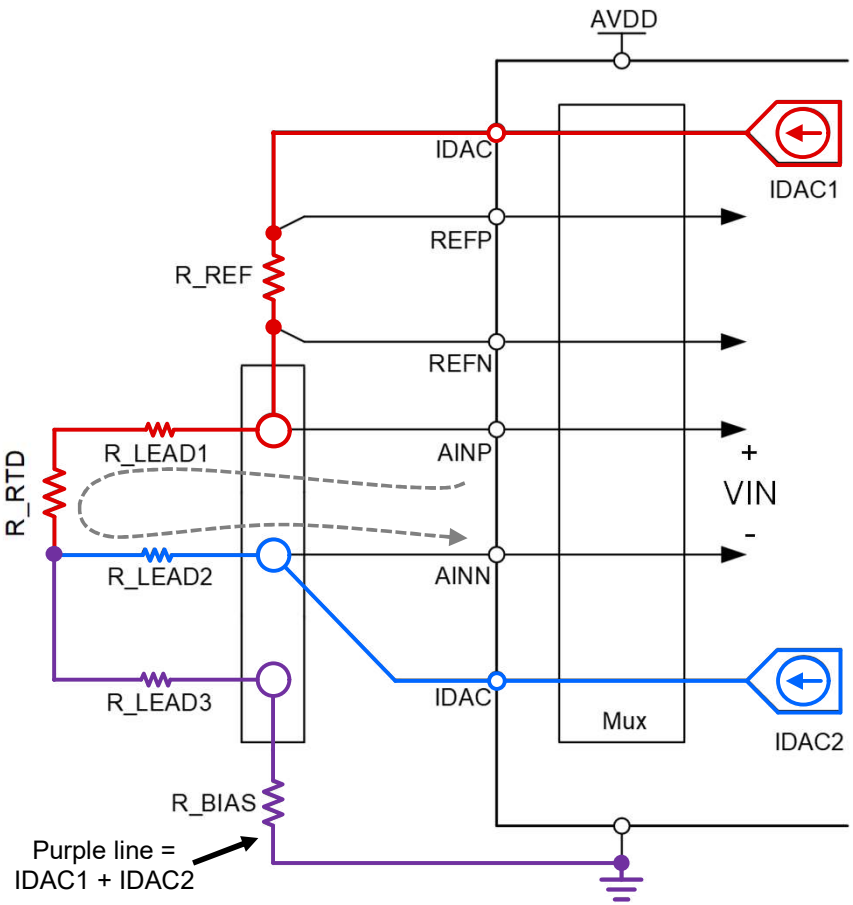
Set the constant 1 = $\frac{2-\text{E}_{\text{IM}}}{2-\text{E}_{\text{IM}}}$

$$\text{ADC error} = \left(\frac{2 - 2 * \text{E}_{\text{IM}}}{2 - \text{E}_{\text{IM}}} - \frac{2 * \text{R\_LEAD} * \text{E}_{\text{IM}}}{\text{R\_RTD} * (2 - \text{E}_{\text{IM}})} - \frac{2 - \text{E}_{\text{IM}}}{2 - \text{E}_{\text{IM}}}\right) * 100\%$$

Simplify and factor out the common variable $\frac{-\text{E}_{\text{IM}}}{2-\text{E}_{\text{IM}}}$

$$\text{ADC error} = \frac{-\text{E}_{\text{IM}}}{2 - \text{E}_{\text{IM}}} * \left(1 + \frac{2 * \text{R\_LEAD}}{\text{R\_RTD}}\right) * 100\%$$

Measuring VIN (3-wire RTD, 2x IDACs, HS R_REF)



$$\underline{\mathrm{VIN} = \mathrm{AINP} - \mathrm{AINN}}$$

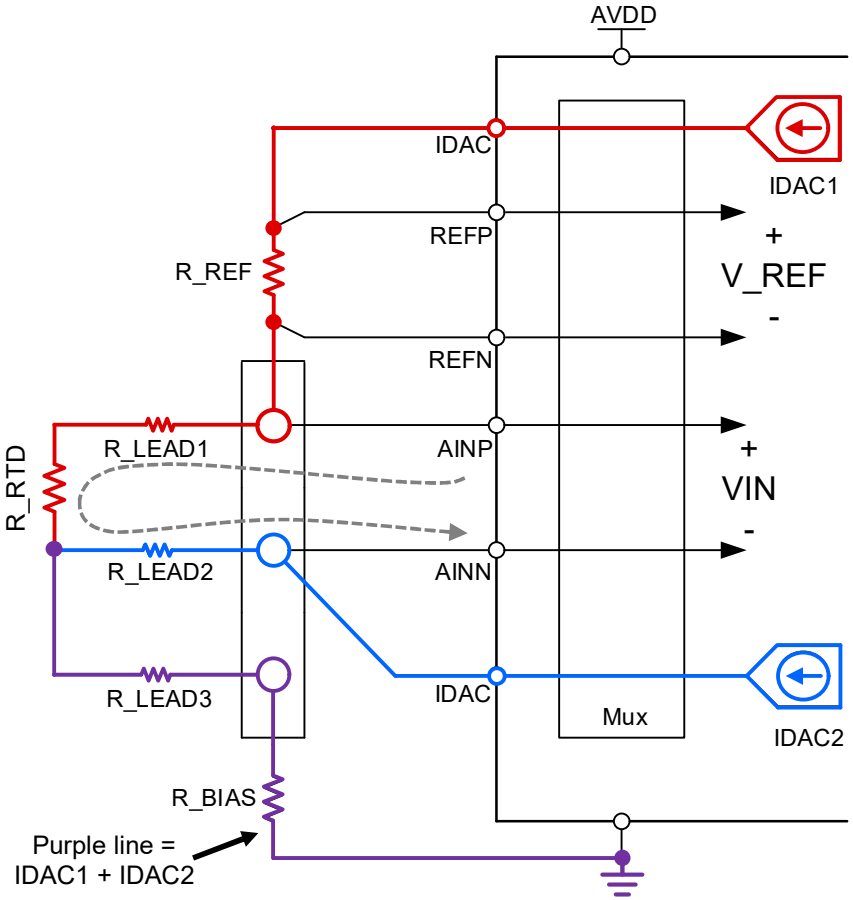
$$\mathrm{VIN} = \mathrm{V\_LEAD1} + \mathrm{V\_RTD} - \mathrm{V\_LEAD2}$$

- $\mathrm{V\_LEAD1} = \mathrm{IDAC1} * \mathrm{R\_LEAD1}$
- $\mathrm{V\_RTD} = \mathrm{IDAC1} * \mathrm{R\_RTD}$
- $\mathrm{V\_LEAD2} = \mathrm{IDAC2} * \mathrm{R\_LEAD2}$

$$\mathrm{VIN} = \mathrm{IDAC1} * (\mathrm{R\_RTD} + \mathrm{R\_LEAD1}) - \mathrm{IDAC2} * \mathrm{R\_LEAD2}$$

(same VIN equation as low-side R_REF configuration)

ADC output code (3-wire RTD, 2x IDACs, HS R_REF)



$$VIN = IDAC1 * (R\_RTD + R\_LEAD1) - IDAC2 * R\_LEAD2$$

$$V\_REF = IDAC1 * R\_REF$$

$$ADC\ code = \frac{VIN}{V\_REF}$$

Assume IDAC1 = IDAC2

$$= \frac{\cancel{IDAC1} * (R\_RTD + R\_LEAD1) - \cancel{IDAC2} * R\_LEAD2}{(\cancel{IDAC1}) * R\_REF}$$

$$= \frac{R\_RTD + \cancel{R\_LEAD1 - R\_LEAD2}}{R\_REF}$$

Assume R_LEAD1 = R_LEAD2

$$= \frac{R\_RTD}{R\_REF}$$

What if IDAC1 ≠ IDAC2?

How IDAC mismatch affects 3-wire RTDs (HS R_REF)

IDAC mismatch error (E_{IM})

$$E_{IM} = 1 - \frac{IDAC1}{IDAC2}$$

$$IDAC1 = IDAC2 * (1 - E_{IM})$$

$$ADC\ code = \frac{IDAC1 * (R\_RTD + R\_LEAD) - IDAC2 * R\_LEAD}{IDAC1 * R\_REF}$$

$$ADC\ code = \frac{IDAC2 * (1 - E_{IM}) * (R\_RTD + R\_LEAD) - (IDAC2 * R\_LEAD)}{[IDAC2 * (1 - E_{IM})] * R\_REF}$$

$$ADC\ code = \frac{R\_RTD - R\_RTD * E_{IM} - R\_LEAD * E_{IM} + R\_LEAD - R\_LEAD}{(1 - E_{IM}) * R\_REF}$$

$$ADC\ code = \frac{R\_RTD * (1 - E_{IM})}{R\_REF * (1 - E_{IM})} - \frac{R\_LEAD * E_{IM}}{(1 - E_{IM}) * R\_REF}$$

$$ADC\ code = \frac{R\_RTD}{R\_REF} - \frac{R\_LEAD * E_{IM}}{R\_REF * (1 - E_{IM})}$$

How much ADC error does IDAC mismatch contribute?

Calculating ADC error due to E_{IM} (HS R_REF)

General form of the error equation

$$\text{ADC error} = \left(\frac{\text{ADC code}_{\text{Mismatch}} - \text{ADC code}_{\text{Ideal}}}{\text{ADC code}_{\text{Ideal}}}\right) * 100\%$$

Apply system-specific expressions

$$\text{ADC error} = \left(\frac{\left[\frac{\text{R\_RTD}}{\text{R\_REF}} - \frac{\text{R\_LEAD} * \text{E}_{\text{IM}}}{\text{R\_REF} * (1 - \text{E}_{\text{IM}})}\right] - \left[\frac{\text{R\_RTD}}{\text{R\_REF}}\right]}{\frac{\text{R\_RTD}}{\text{R\_REF}}}\right) * 100\%$$

Divide out R_REF

$$\text{ADC error} = \left(\frac{\left[\text{R\_RTD} + \frac{\text{R\_LEAD} * \text{E}_{\text{IM}}}{1 - \text{E}_{\text{IM}}}\right] - \text{R\_RTD}}{\text{R\_RTD}}\right) * 100\%$$

Divide each term by R_RTD

$$\text{ADC error} = \left(\left[\frac{\text{R\_RTD}}{\text{R\_RTD}} + \frac{\text{R\_LEAD} * \text{E}_{\text{IM}}}{\text{R\_RTD} * (1 - \text{E}_{\text{IM}})}\right] - \frac{\text{R\_RTD}}{\text{R\_RTD}}\right) * 100\%$$

Simplify

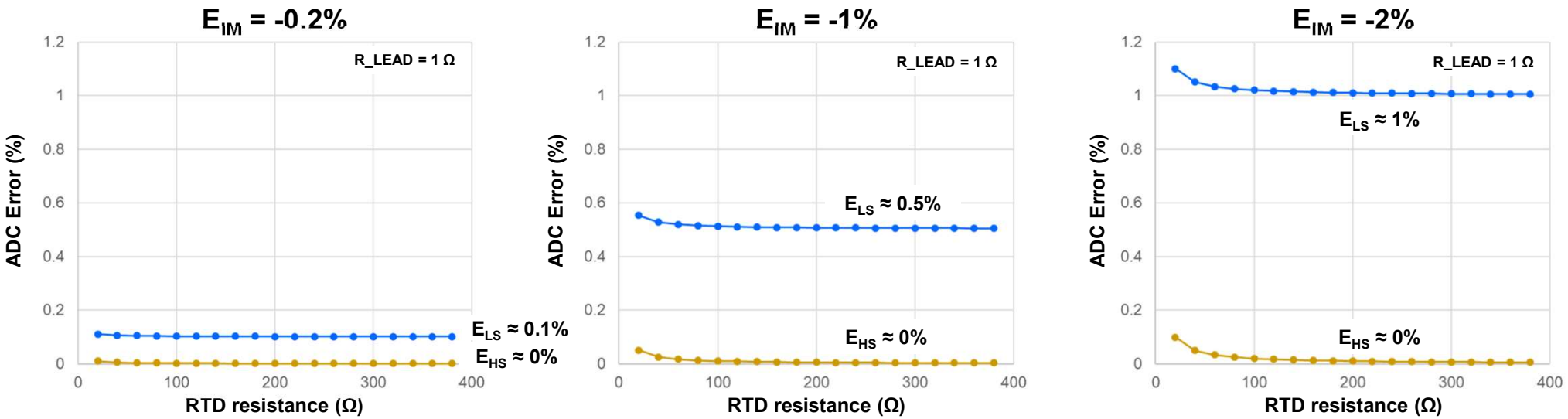
$$\text{ADC error} = \frac{\text{E}_{\text{IM}}}{1 - \text{E}_{\text{IM}}} * \left(\frac{\text{R\_LEAD}}{\text{R\_RTD}}\right) * 100\%$$

Comparing errors due to E_{IM} (LS R_REF & HS R_REF)

Condition	ADC Error		Comment
	Low-side R_REF	High-side R_REF	
General form	$= \frac{-E_{IM}}{2 - E_{IM}} * \left(1 + \frac{2 * R\_LEAD}{R\_RTD}\right) * 100\%$	$= \frac{E_{IM}}{1 - E_{IM}} * \left(\frac{R\_LEAD}{R\_RTD}\right) * 100\%$	
E_{IM} is small (<2%)	$\approx \frac{-E_{IM}}{2} * \left(1 + \frac{2 * R\_LEAD}{R\_RTD}\right) * 100\%$	$\approx E_{IM} * \left(\frac{R\_LEAD}{R\_RTD}\right) * 100\%$	Typical E_{IM} values are very small e.g. ADS124S08 = 0.15%
R_RTD ≈ R_LEAD	$\approx -\frac{3}{2} * E_{IM} * 100\%$	$\approx E_{IM} * 100\%$	When R_RTD is small, the LS R_REF error due to E_{IM} is 1.5x larger compared to the HS R_REF
R_RTD >> R_LEAD	$\approx -\frac{1}{2} * E_{IM} * 100\%$	$\approx 0\%$	When R_RTD is large, a HS R_REF has virtually no error due to E_{IM}

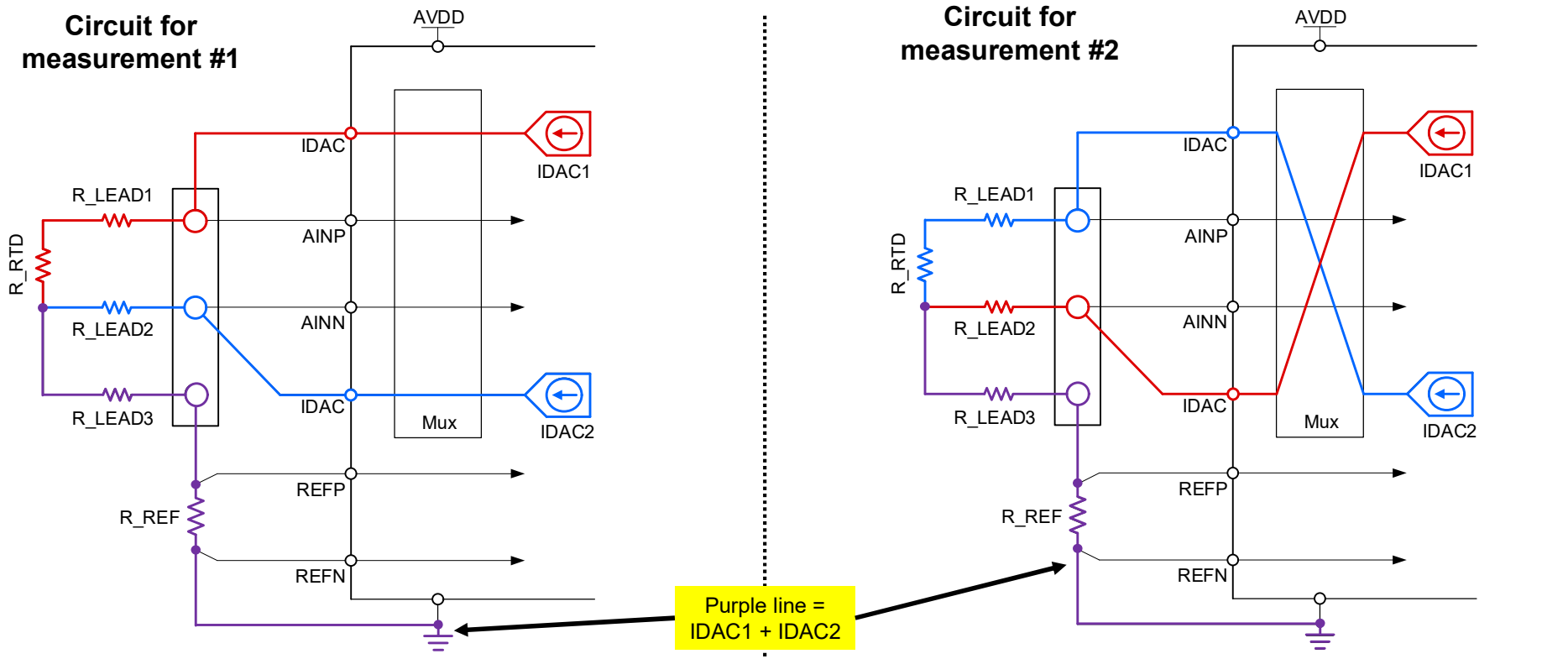
Plotting errors due to E_{IM} (LS R_REF & HS R_REF)

Low-side R_REF	High-side R_REF
$= \frac{-E_{IM}}{2 - E_{IM}} * \left(1 + \frac{2 * R\_LEAD}{R\_RTD}\right) * 100\% \approx -\frac{1}{2} * E_{IM} * 100\%$	$= \frac{E_{IM}}{1 - E_{IM}} * \left(\frac{R\_LEAD}{R\_RTD}\right) * 100\% \approx 0\%$



Choose high-side R_REF if possible

How IDAC chop works (LS R_REF)



$$\text{ADC Code \#1} = \frac{\text{IDAC1} * (\text{R\_RTD} + \text{R\_LEAD1}) - \text{IDAC2} * \text{R\_LEAD2}}{\text{R\_REF} * (\text{IDAC1} + \text{IDAC2})}$$

$$\text{ADC Code \#2} = \frac{\text{IDAC2} * (\text{R\_RTD} + \text{R\_LEAD1}) - \text{IDAC1} * \text{R\_LEAD2}}{\text{R\_REF} * (\text{IDAC1} + \text{IDAC2})}$$

Calculating the IDAC chop result

General form of the error equation

$$ADC\ code = \frac{\text{Measurement \#1} + \text{Measurement \#2}}{2}$$

Apply system-specific expressions

$$ADC\ code = \frac{\left(\frac{IDAC1 * (R\_RTD + R\_LEAD1) - IDAC2 * R\_LEAD2}{R\_REF * (IDAC1 + IDAC2)} + \frac{IDAC2 * (R\_RTD + R\_LEAD1) - IDAC1 * R\_LEAD2}{R\_REF * (IDAC1 + IDAC2)}\right)}{2}$$

Combine all IDAC1 and IDAC2 terms

$$ADC\ code = \frac{IDAC1 * (R\_RTD + R\_LEAD1 - R\_LEAD2) + IDAC2 * (R\_RTD + R\_LEAD1 - RLEAD2)}{2 * R\_REF * (IDAC1 + IDAC2)}$$

Factor out the (R_RTD + R_LEAD1 – R_LEAD2) term

$$ADC\ code = \frac{(R\_RTD + R\_LEAD1 - R\_LEAD2) * (IDAC1 + IDAC2)}{2 * R\_REF * (IDAC1 + IDAC2)}$$

Simplify assuming R_LEAD1 = R_LEAD2

$$ADC\ code = \frac{R\_RTD * (IDAC1 + IDAC2)}{2 * R\_REF * (IDAC1 + IDAC2)}$$

Reduces to ideal ADC output code equation

$$ADC\ code = \frac{R\_RTD}{2 * R\_REF}$$

Thanks for your time!
Please try the quiz.

Quiz: Challenges with 3-wire RTD systems

1. (T/F) Measuring 3-wire RTDs using one IDAC generally has lower error compared to using two IDACs because the two IDAC method introduces IDAC mismatch errors.
   a) True
   b) False

2. When measuring 3-wire RTDs using two IDACs, which configuration has the lowest error?
   a) Low-side reference configuration
   b) High-side reference configuration

3. (T/F) Measuring 3-wire RTDs using two IDACs is faster compared to using one IDAC because the two IDAC method only requires one measurement.
   a) True
   b) False

Quiz: Challenges with 3-wire RTD systems

4. What is IDAC chop used for?
   a) It is used to effectively cut the IDAC into multiple equal sized pieces
   b) It is a method used on single IDAC measurements where the IDAC is pulse-width modulated
   c) It is used to remove IDAC mismatch in 3-wire, two IDAC systems by taking one measurement, then swapping the position of the IDACs, taking another measurement, and finally averaging the results

5. What is the disadvantage of IDAC chop?
   a) Two measurements are required, which increases measurement time
   b) It always requires an external multiplexer
   c) It can lead to uncontrolled oscillations

Thanks for your time!