Debugging a Current Shunt Monitor Circuit – Overlooking Device Specifications

TI Precision Labs – Current Sense Amplifiers

Presented and Prepared by Patrick Simmons

Hello, and welcome to the TI precision labs series on current sense amplifiers. My name is Patrick Simmons, and I’m an applications engineer in the Current Sensing & Position Sensing product line. In this video, we continue our discussion on debug, this time focusing on some of the errors resulting from overlooked specifications.

Sources of Error

Device Errors:

$$\varsigma_{RSS}(\%) \approx \sqrt{{e_{Vos}}^2 + {e_{CMRR}}^2 + {e_{PSRR}}^2 + {e_{Gain\_error}}^2 + {e_{Linearity}}^2 + {e_{Shunt\_tolerance}}^2 + {e_{Bias\_current}}^2 + {e_{Other}}^2}$$

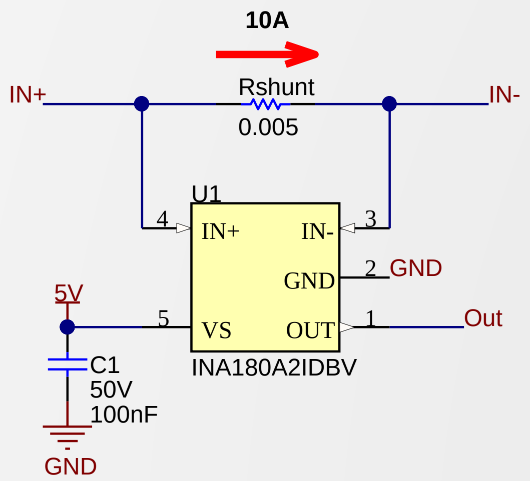
User Errors:

- Improper Layout
- Probe Placement
- Solder issues
- Overlooking device specifications
- Downstream circuitry
- Equipment and Settings
- Actual Fails

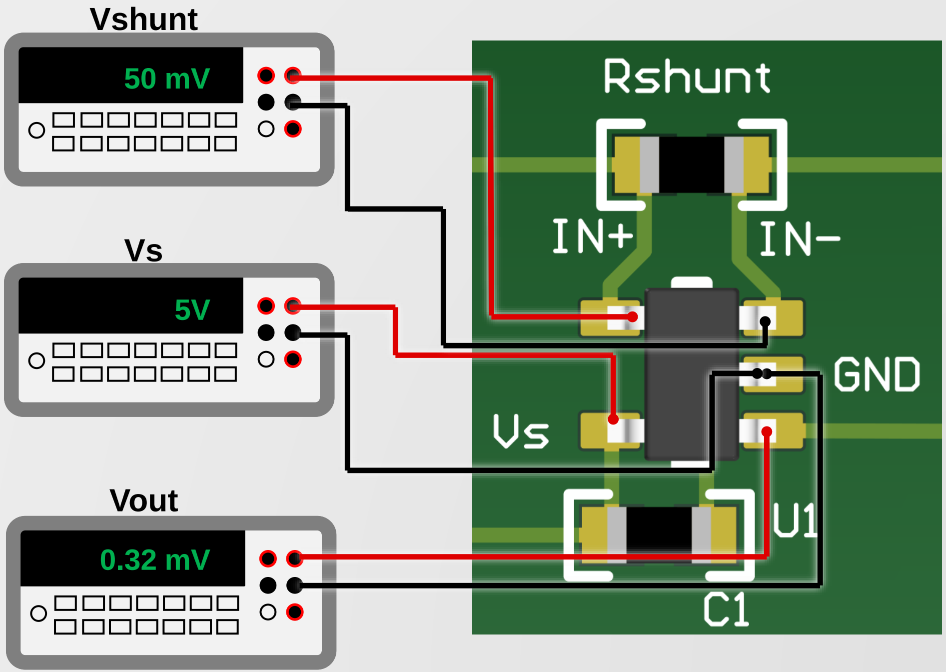
Having in prior videos covered layout, probe placement, and solder issues, we will now focus on some of the errors that arise from overlooking certain device specifications.

Overlooking Specification: Case 1

Conditions



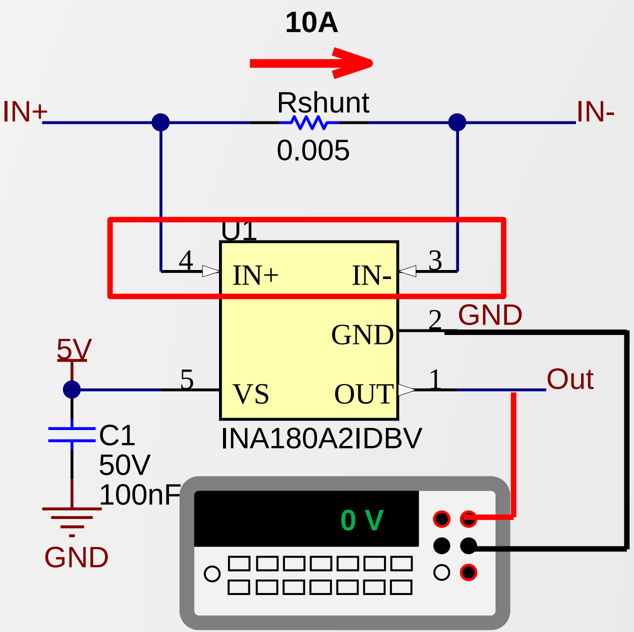
$$Expected\ V_{out} = 50mV \times 50\frac{V}{V} = 2.5V$$

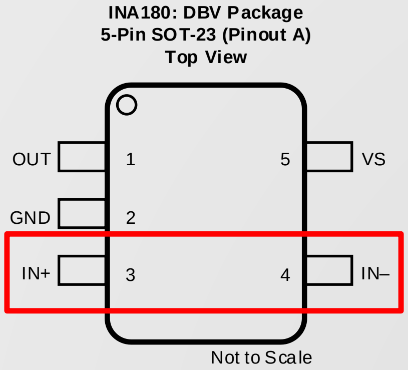


For our first example, we are trying to measure 10A across a 5mΩ shunt with a 50V/V gain INA180. We expect 2.5V output, yet we measure 0.32mV. That is a huge difference. With a 5V supply, we know there should not be any issues . So what are we overlooking?

Overlooking Specification: Case 1

Source of Error



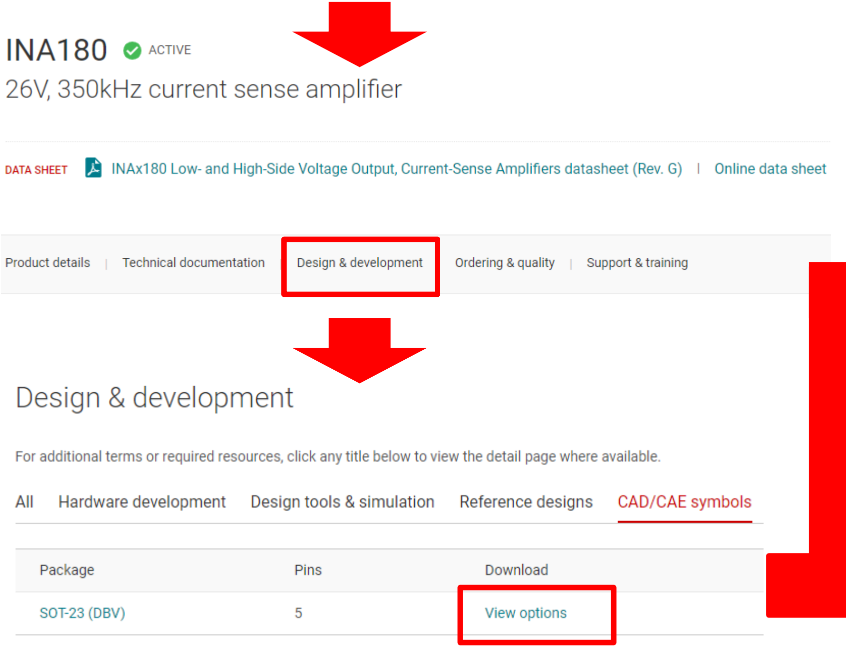


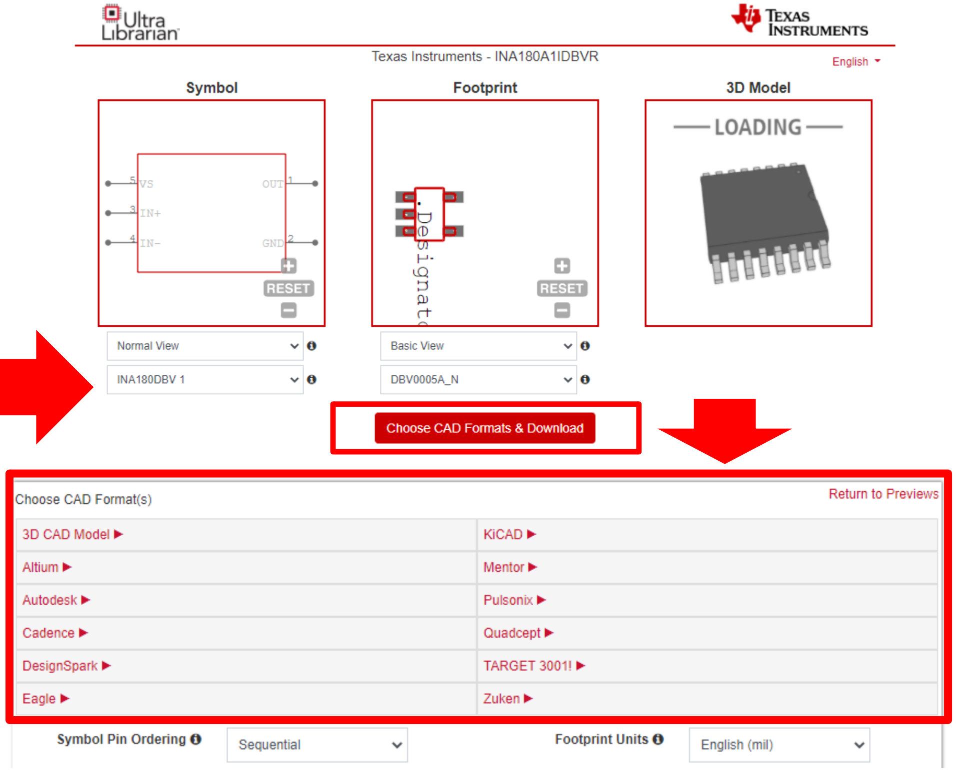
In this case, it turns out to be something quite simple. Whoever made the part for the layout program accidentally swapped the input pins. Since the INA180 is a unidirectional device, when the current flows in the reverse direction the output rails to the ground, making the device look like it is not working.

A related mistake to this is swapping the polarity of your wires when bread boarding or drawing your board traces. While these are simple mistakes, they are also easy to over look. Be sure to quickly rule out these kind of mistakes early and save yourself from embarrassment lest you resort to asking your colleague for an opinion on why your device is not working.

Downloading Schematic, footprint, and 3d model

Go to ti.com, and search for part





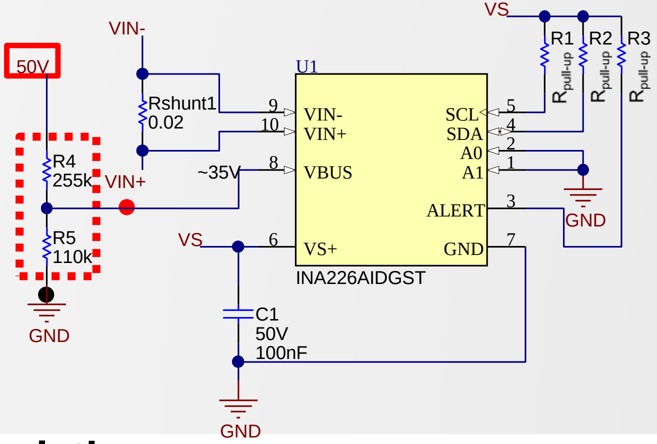
TI conveniently has schematic symbols, footprints, and 3D models available for many of our devices, which can help you save time and avoid mistakes like the last example. To download our vetted models, go to ti.com, then on the device web page click Design and development, and then select the CAD/CAE symbols tab so that you can click the view options link. From there you will be directed to our Ultra Librarian model repository. As you can see, we accommodate several different layout programs.

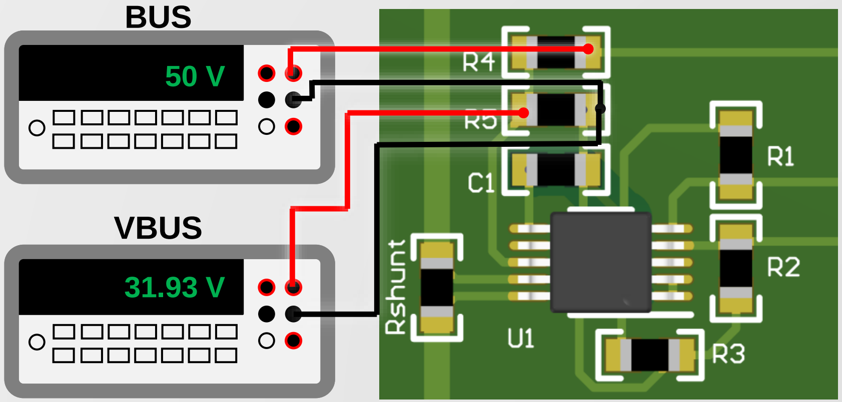
Overlooking Specification: Case 2

Design Constraint

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
Bus voltage input range		0		36	V

Conditions





Calculations

$$V_{Bus\_Ideal} = BUS \times \frac{R5}{R4 + R5} = 50V \times \frac{255k\Omega}{255k\Omega + 110k\Omega} = 34.93V$$

Now lets look at a case where we are attempt to get a little creative to get around a device limitation. In this instance we have a 50V bus and we want to use the INA226 to help use take a power measurement. Unfortunately we are constrained to 36V max for a bus measurement. Consequently we decide to use a voltage divider to scale down the bus and plan to use a scaling factor in the post processing. Upon testing our layout we find the measured bus is several volts off from what we expect despite using low tolerance resistors in our divider. So what specification are we overlooking?

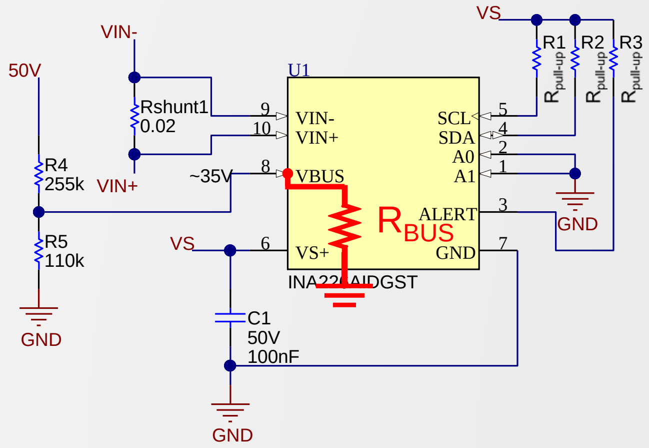
Overlooking Specification: Case 2

Source of Error

6.5 Electrical Characteristics

at T_A = 25 °C, V_S = 3.3V, V_{IN+} = 12 V, V_{SENSE} = (V_{IN+} - V_{IN-})= 0 mV and VBUS = 12 V, unless otherwise noted

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
VBUS input impedance		-15%	830	+15%	kΩ



$$V_{Bus} = BUS \times \frac{R5}{R4 + R5||R_{BUS}}$$

$$= 50V \times \frac{255k\Omega}{110k\Omega + 255k\Omega||830k\Omega}$$

$$= 31.97V$$

In this particular case, we should have considered the bus input impedance, which in this instance is a resistance.
After accounting for the typical INA226 bus resistance, we calculate 31.97V for an expected bus voltage, which is pretty close to what we measured. The difference can be attributed to the tolerance of this input bus resistance.

While not stated in the datasheet, the tolerance may be around ±15%. Consequently, if you are looking for precise measurements, you may need to consider another part with a higher bus voltage specification.

Overlooking Specification: Case 3

Design Constraints

$100\mu A \leq Load \leq 2A$

$Power\ dissipated\ across\ RSHUNT < 30mW$

$Device\ Used: INA226$

Test Condition

$Max\ Conversion\ Time$

$Max\ Number\ of\ Averages$

$100\mu A\ from\ Eload$

Design

$$Current\ LSB\ size = \frac{Maximum\ Expected\ Current}{2^{15}} = \frac{2A}{2^{15}} = 61.035\mu A$$

$$61.035\mu A < 100\mu A$$ ✔

$$P_{SHUNT\ Max} = R_{SHUNT} \times Load_{Max} = 10m\Omega \times 2A = 20mW$$

$$20mW < 30mW$$ ✔

$$CAL = \frac{0.00512}{Current\_LSB \times R_{SHUNT}} = \frac{0.00512}{61.035\mu A \times 10m\Omega} = 8388.6 \approx 8389$$

$$Current\_LSB = \frac{0.00512}{CAL \times R_{SHUNT}} = 61.0323\mu A$$

I2C Read Back

Register	Binary	Hex	Decimal
Calibration Register	0010000011000101	20C5	8389
Configuration Register	0100111000111101	4E3D	20029
Current Register	0000000000000100	0004	4

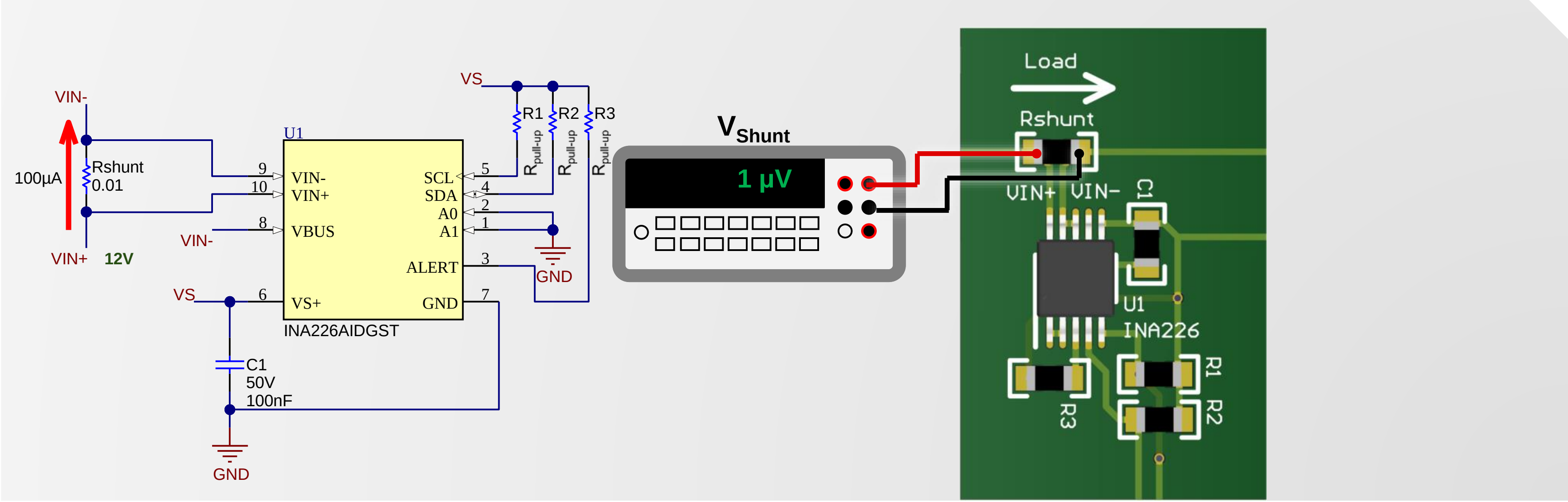
$$Load_{measured} = Current\ LSB\ size \times current\ register\ value$$

$$= 61.0323\mu A \times 4 = 244.14\mu A$$

While on the topic of power monitors, lets look at another example involving the INA226. In this case we are told we need to be able to measure 100uA to 2A and keep the power dissipated across the shunt to 30mW. While investigating the part, we find some useful design formulas. One we use to calculate the LSB value for our current register when the max current is 2A. From that calculation we see that we get value that is below the range minimum. As we conveniently have several 10mΩ resistors on hand, we decide to use those, especially since they yield a power dissipation for 2A that is below 30mW. Based upon that shunt we get a CAL value of roughly 8389, which we use to back-calculate the adjusted current_LSB. We thereupon write the CAL value to our calibration register and specify we will be taking the max conversion time and max number of averages for the shunt voltage measurements in our configuration register. After writing to the device register source 100uA across our shunt from e-load. To our dismay, we read that the INA226 is measuring 244uA. What is wrong with our part?

Overlooking Specification: Case 3

Conditions



Calculations

$$V_{Shunt\ calculateed} = Current_{LSB} \times current\ register\ value \times R_{shunt} = 61.0323\mu A \times 4 \times 0.01\Omega = 2.44\mu V$$

We decide to probe across our shunt and we do see that it is in fact 1uV as it should be. Yet if we back calculate what our measured shunt voltage is from our current register value, we get 2.44uV. This is nearly double the actual value. Did we overlook something in our configuration?

Overlooking Specification: Case 3

Source of Error

6.5 Electrical Characteristics

at T_A = 25 °C, V_S = 3.3V, V_{IN+} = 12 V, V_{SENSE} = (V_{IN+} - V_{IN-})= 0 mV and VBUS = 12 V, unless otherwise noted

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
INPUT						
V_{OS}	Shunt offset voltage, RTI			±2.5	±10	µV
1 LSB step size		Shunt voltage		2.5		µV
		Bus voltage		1.25		mV

$$I_{Sense\ Min} = \frac{1\ LSB\ Shunt\ voltage}{R_{SHUNT}} = \frac{2.5\mu V}{10m\Omega} = 250\mu A$$

$$Current\ Register = \frac{I_{Sense\ Min}}{Current\_LSB} = \frac{250\mu A}{61.0323\mu A} = 4.1 \approx 4 LSBs$$

$$1\ Shunt\ voltage\ register\ LSB \approx 4\ Current\ Register\ LSBs$$

$$V_{OS} = \frac{\pm 2.5\mu V}{2.5\mu V/LSB}\ up\ to\ \frac{\pm 10\mu V}{2.5\mu V/LSB} = \pm 1\ shunt\ voltage\ LSB\ up\ to\ \pm 4\ shunt\ voltage\ LSB$$

$$= \pm 4\ current\ LSB\ up\ to\ \pm 8\ current\ LSB$$

Yes, it turns out that we overlooked the 1LSB step size for the shunt voltage as well as the offset voltage specifications. The minimum shunt voltage is 2.5uV. If we divide that by our shunt value, we find that actually 250uA is the lowest we could hope to measure and that corresponds to 4 LSBs. In reality there will likely be some voltage offset and we should expect the output to be even higher. With offset voltage we might see 4 to 8 LSBs for the CAL setting we chose in this situation.

Overlooking Specification: Case 4

Design Constraints

$Monitor\ Power$

$Load \leq 20A$

Design

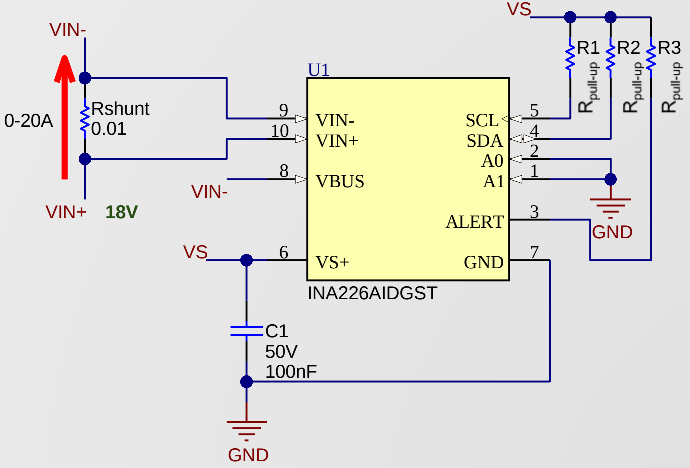
$$Current_{LSB} = \frac{Maximum\ Expected\ Current}{2^{15}} = \frac{20A}{2^{15}} = 610\mu A$$

$$R_{Shunt} = \frac{1\ LSB\ Shunt\ Voltage}{Current\_LSB} = \frac{2.5\mu V}{610\mu A} = 4.098m\Omega$$

Decide 10mΩ is close enough

$$CAL = \frac{0.00512}{Current\_LSB \times R_{SHUNT}} = \frac{0.00512}{610\mu A \times 10m\Omega} = 839$$

Current and power register scaled according to CAL

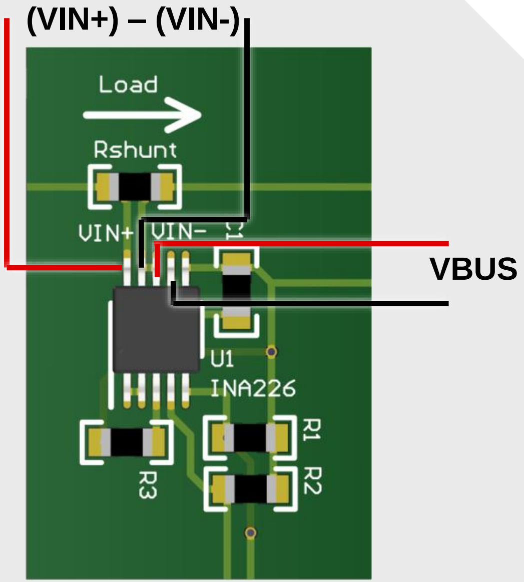


We have yet another case involving a INA226 power monitor. In this instance, we would like to measure up to at least 20A. In this case we use the current LSB as before and this time calculate what our corresponding shunt value is, roughly 4mΩ. We don't have a 4mΩ on hand, but we figure 10mΩ is close enough and will even give us better minimum resolution, so we proceed with that value to calculate CAL.

After writing this value to the Calibration registers, the INA226 will scale the current and power registers according to the maximum expected current.

Overlooking Specification: Case 4

Conditions



We subsequently try to hook up our INA226 and run through a series of measurements to see if we get what we expect. Around 10A we begin to see some behavior we were not expecting. The power appears to plateau despite our external meters indicating that both the bus and current levels are rising. Did we possibly setup the device incorrectly?

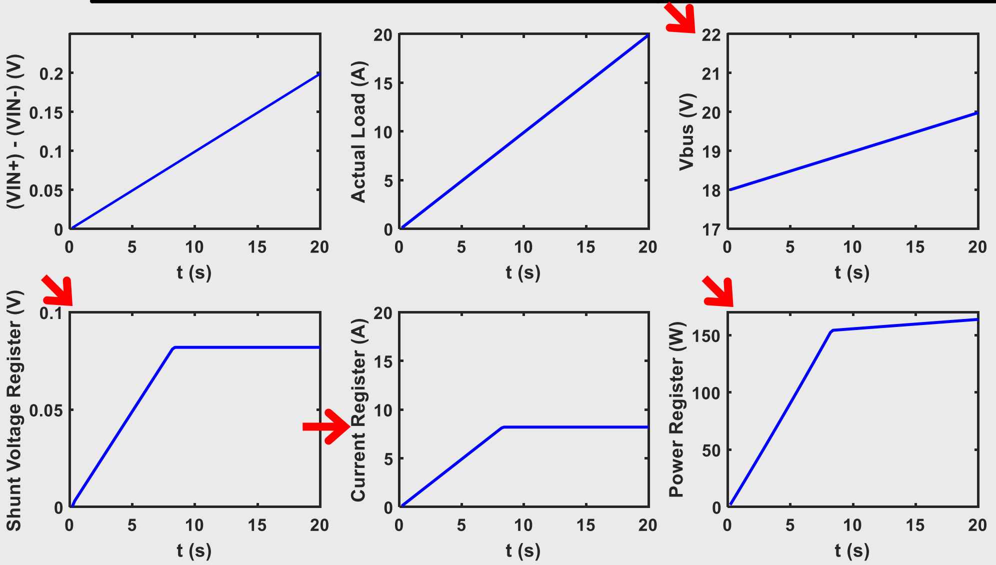
Overlooking Specification: Case 4

Source of Error

6.5 Electrical Characteristics

at T_A = 25 °C, V_S = 3.3V, V_{IN+} = 12 V, V_{SENSE} = (V_{IN+} - V_{IN-})= 0 mV and VBUS = 12 V, unless otherwise noted

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
INPUT					
Shunt voltage input range		-81.9175		81.92	mV



$$Max\ Vsense = 20A \times 10m\Omega = 0.2V$$

$$Max\ I_{measured} = shunt\ voltage\ input_{max} \div R_{shunt}$$

$$= 81.92mV \div 10m\Omega = 8.192A$$

CHECK

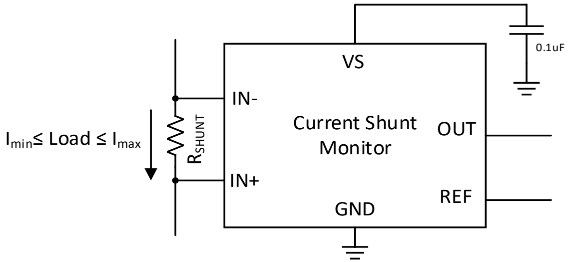
- Shunt Voltage Register
- Bus Voltage Register

$$R_{Shunt\ Max} = \frac{Shunt\ voltage\ input\ range}{Max\ I_{measured}}$$

Yes, by choosing a shunt larger than 4mΩ, we lowered the minimum current we can detect, yet we nearly halved the max current we can detect due to the shunt voltage input range limitation of the device. To see this more readily, we should look at the registers upon which the power register is calculated. By looking at the shunt voltage register and the bus register we are able to see why the power register exhibits the curve we observed. To avoid this problem we should verify that our shunt resistor is below the shunt max value.

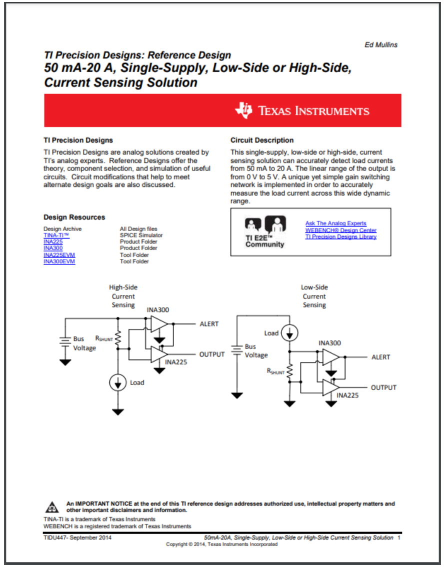
Measurement Range Exceeds Device Bounds

- **Analog Current Monitor Constraints:**
  - $I_{max} \leq \frac{(V_S - Swing\ to\ V_S) - V_{ref}}{Gain \times R_{shunt}}$ or $I_{max} \leq \frac{V_{ref} - Swing\ to\ GND}{Gain \times R_{shunt}}$
  - $I_{min} \geq \frac{V_{OS}}{R_{shunt}}$ and $I_{min} \geq I_B$
- **Digital Current Monitor Constraints:**
  - $I_{max} \leq \frac{Shunt\ voltage\ input\ range}{R_{shunt}}$
  - $I_{min} \geq \frac{V_{OS}}{R_{shunt}}$ and $I_{min} \geq \frac{Shunt\ voltage\ LSB\ step\ size}{R_{shunt}}$



FIX:

- Increase supply
- Adjust ADC configuration settings
- Replace with a part that has lower V_{OS} and I_B
- Multiplex shunt resistors
- Adjust gain settings



Ed Mullins

TI Precision Designs: Reference Design

50 mA-20 A, Single-Supply, Low-Side or High-Side, Current Sensing Solution

Texas Instruments

TI Precision Designs

TI Precision Designs are analog solutions created by TI's analog experts. Reference Designs offer the theory, component selection, and simulation of useful circuits. Circuit modifications that help to meet alternate design goals are also discussed.

Circuit Description

This single-supply, low-side or high-side, current sensing solution can accurately detect load currents from 50 mA to 20 A. The linear range of the output is from 0 V to 5 V. A unique yet simple gain switching network is implemented in order to accurately measure the load current across this wide dynamic range.

Design Resources

Design Archive	All Design files
TINA-TI™	SPICE Simulator
INA225	Product Folder
INA300	Product Folder
INA225EVM	Tool Folder
INA300EVM	Tool Folder

TI E2E™ Community

Ask The Analog Experts
WEBENCH® Design Center
TI Precision Designs Library

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TIDU447- September 2014 *50mA-20A, Single-Supply, Low-Side or High-Side Current Sensing Solution* 1

So as you may have gathered from the last two examples, it is important to observe the input limits of the current shunt monitor device. As current range depends on multiple variables, we typically do not have a current range specification in the datasheet. However, the feasible range can be determined given certain conditions from your design. Here is a basic summary of bounding constraints for both our analog and digital monitor devices.

During an initial assessment with the device, you might encounter some challenges with getting a wide enough measurement range. For our analog devices, increasing the supply within the recommended operating range might help. As for our digital devices, it might be as simple as changing a configuration setting for the ADC. However, if these simple approaches still fall short, then you may need to consider another device, one that has lower input voltage offset and input bias current. Lastly, if another part does not provide the range you need, you will need to get a little creative, with multiplexing through shunt resistors or adjusting gain settings such as in this TI design.

Summary

- Double-check pin out and absolute max ratings
- TI has layout models available online
- Account for internal device impedances
- Verify device within recommended operating range
- For digital power monitors, first verify shunt and bus voltages, before power
- A clearly specified current range is typically not listed in the datasheet
- Current range of the device for your operating conditions can be quickly determined from Datasheet specification

In summary, checking the device pin out and abs max table may reveal a simple mistake.

To help minimize layout mistakes, TI offers premade models online.

When laying out the current shunt monitors, remember that the current monitors are complex circuits with finite internal impedances that can interact with whatever network they are interfaced with. As such, these impedances are often documented in the datasheet. Along with the impedance are several other specifications in the electrical characteristics, which you should check to insure you are operating in the normal linear operating range. While working with power monitors, first debug the fundamental measurements like shunt and bus voltages before proceeding to calculated values like current and power. While current range is not listed online nor in the datasheet, it can be derived from you operating conditions and device specs.

To find more current sense amplifier technical resources and search products, visit ti.com/currentsense

That concludes this video - thank you for watching! Please try the quiz to check your understanding of the content.

For more information and videos on current sense amplifiers please visit ti.com/currentsense.

Debugging a Current Shunt Monitor Circuit – Overlooking Device Specifications

TI Precision Labs – Current Sense Amplifiers

QUIZ

Debugging a Current Shunt Monitor – Overlooking Device Specs – Quiz

1. Customer has 5000 INA381A2 devices that have a voltage offset referred to the input that is within ±20% of the typical. However, they have found a few outliers that are within ± 200% of the typical value. What might be the issue?
   a) The common mode is different
   b) The supply is different
   c) The temperature is different
   d) There is no issue
   e) All of the above.
   f) None of the above

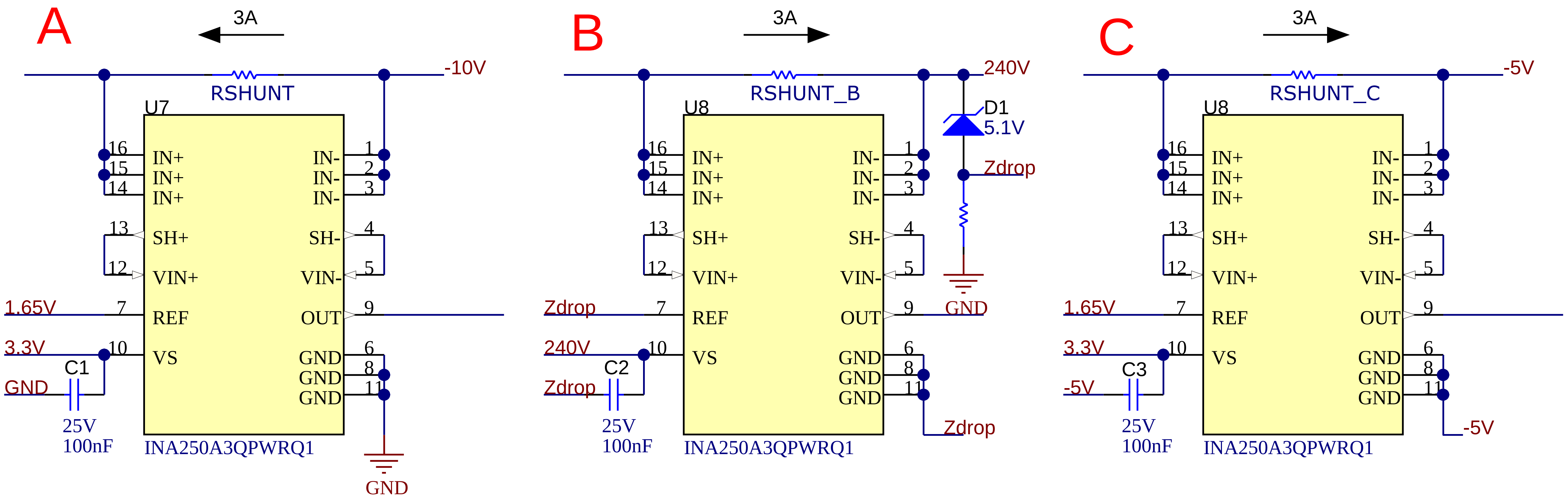
Debugging a Current Shunt Monitor – Overlooking Device Specs – Quiz

2. Which of the following will fail?
   a) A
   b) B
   c) C
   d) A, B
   e) A, C
   f) B, C
   g) A, B, and C

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)[1]

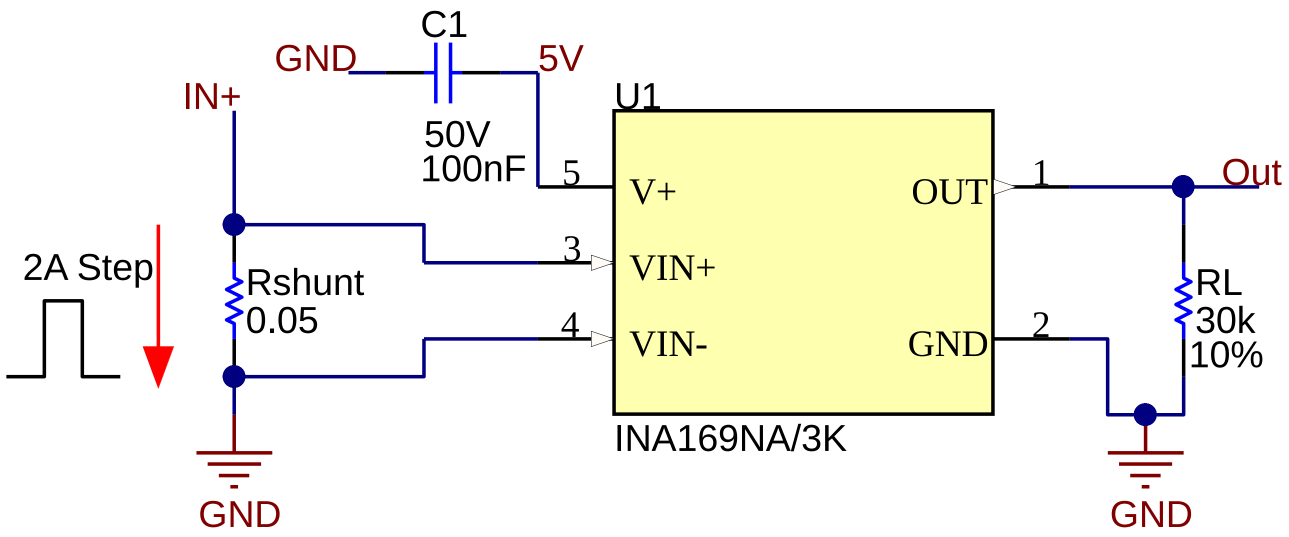
		MIN	MAX	UNIT
Supply voltage (VS)			40	V
Analog input current	Continuous current		±15	A
Analog inputs (IN+, IN–)	Common-mode	GND – 0.3	40	V
Analog inputs (VIN+, VIN–)	Common-mode	GND – 0.3	40	V
	Differential $(V_{IN+}) – (V_{IN-})$	–40	40	
Analog inputs (REF)		GND – 0.3	VS + 0.3	V
Analog outputs (SH+, SH–)	Common-mode	GND – 0.3	40	V
Analog outputs (OUT)		GND – 0.3	(VS + 0.3) up to 18	V
Temperature	Operating, T_A	–55	150	°C
	Junction, T_J		150	
	Storage, T_{stg}	–65	150	



Debugging a Current Shunt Monitor – Overlooking Device Specs – Quiz

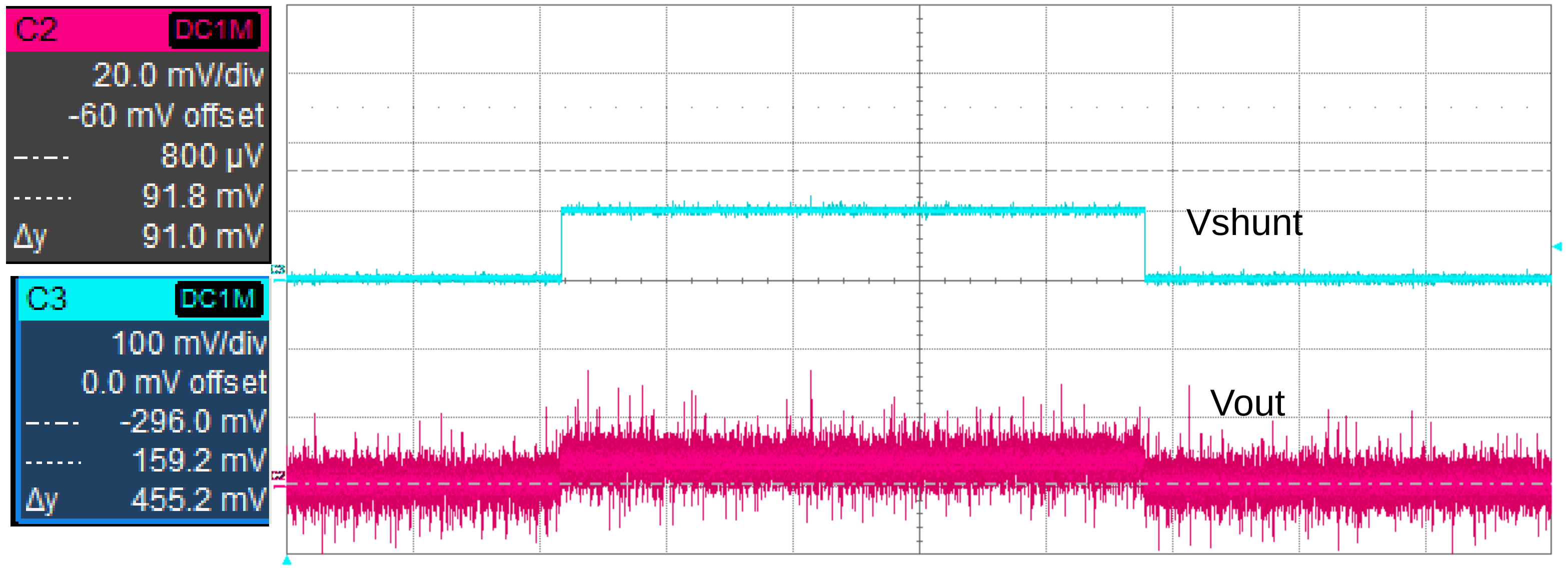
3. When applying a step response to the INA169, a relatively small output is seen on the output given that the output is expected to be $I_{Shunt}R_{Shunt}R_L$ /1kΩ. With the given details, what is likely the issue?

   a) A defective part
   b) Supply voltage is too low
   c) The common mode is outside of the recommended range
   d) Supply voltage is too high
   e) The current is too low.



1 Features

- Complete Unipolar High-Side Current Measurement Circuit
- Wide Supply and Common-Mode Range
- INA139: 2.7 V to 40 V
- INA169: 2.7 V to 60 V
- Independent Supply and Input Common-Mode Voltages
- Single Resistor Gain Set
- Low Quiescent Current: 60 μA (Typical)
- 5-Pin, SOT-23 Packages

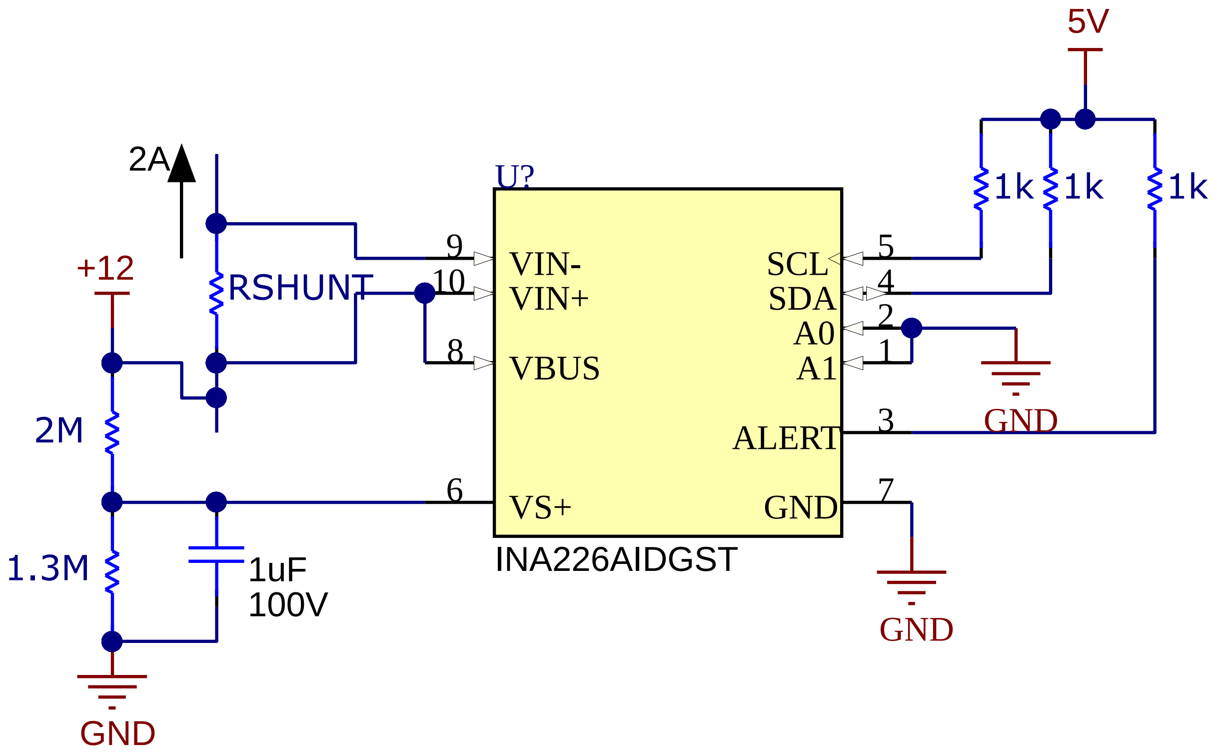


Debugging a Current Shunt Monitor – Overlooking Device Specs – Quiz

4. The device below displays an erroneous shunt voltage value 0.47s after power up. Each power-up leads to a different initial incorrect measurement. Default configuration register values are used. What might be the issue?

   a) Open GND
   b) I2C resistor values
   c) Supply voltage
   d) Conversion Setting

POINTER ADDRESS			POWER-ON RESET		
HEX	REGISTER NAME	FUNCTION	BINARY	HEX	TYPE[1]
00h	Configuration Register	All-register reset, shunt voltage and bus voltage ADC conversion times and averaging, operating mode.	01000001 00100111	4127	R/$\overline{W}$



Answers

Debugging a Current Shunt Monitor – Overlooking Device Specs – Quiz

1. Customer has 5000 INA381A2 devices that have a voltage offset referred to the input that is within ±20% of the typical. However, they have found a few outliers that are within ± 200% of the typical value. What might be the issue?
   a) The common mode is different
   b) The supply is different
   c) The temperature is different
   d) There is no issue
   e) All of the above.
   f) None of the above

±20% equates to a Vos ±120uv, while ±200% corresponds to ±300uV. While the perceived outliers seem significantly larger and possibly inconvenient, these are still within the specifications. Different manufacturing sites and different lots produce devices that are not exactly identical. Yet all devices will be screened and should be within the specification range.

Debugging a Current Shunt Monitor – Overlooking Device Specs – Quiz

2. Which of the following will fail?

a) A
b) B
c) C
d) A, B
e) A, C
f) B, C
g) A, B, and C

Option A violates the common-mode specification for the input pins. The Zener diode keeps device B's and potential such that the common mode voltage and supply voltages = ~5V, well within the absolute max range. For device C, the common mode voltage is 0V and the supply voltage is 8.3V relative to device ground, thereby having the device operate well within the abs max range.

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)

		MIN	MAX	UNIT
Supply voltage (VS)			40	V
Analog input current	Continuous current		±15	A
Analog inputs (IN+, IN–)	Common-mode	GND – 0.3	40	V
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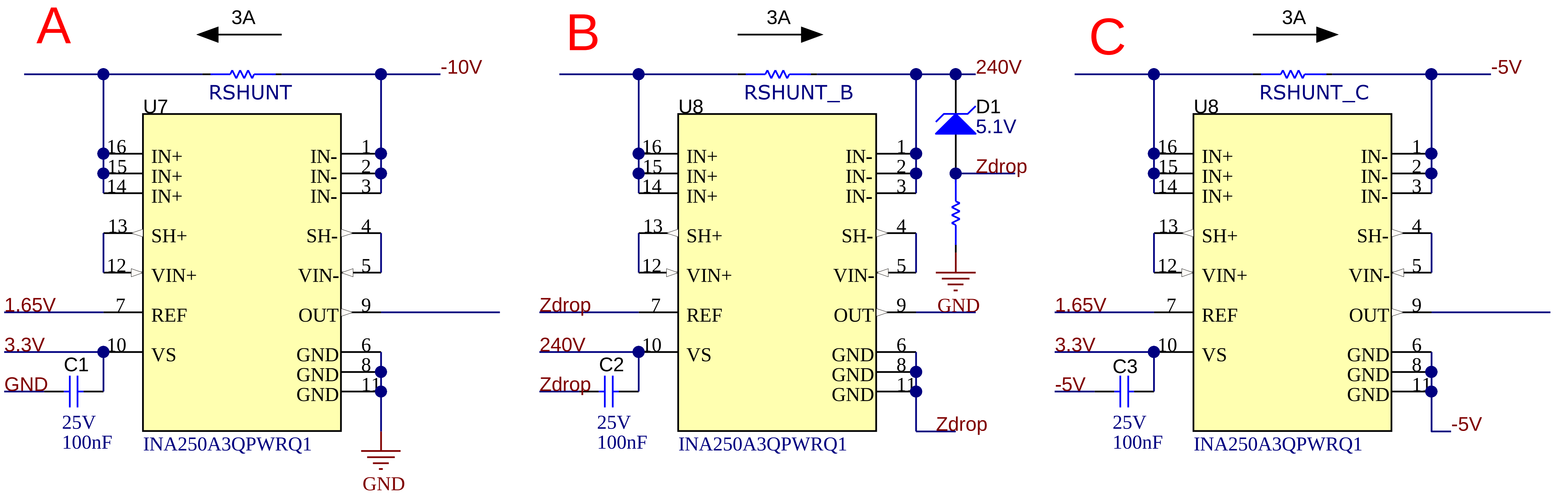
	Junction, T_J		150	
	Storage, T_{stg}	–65	150	

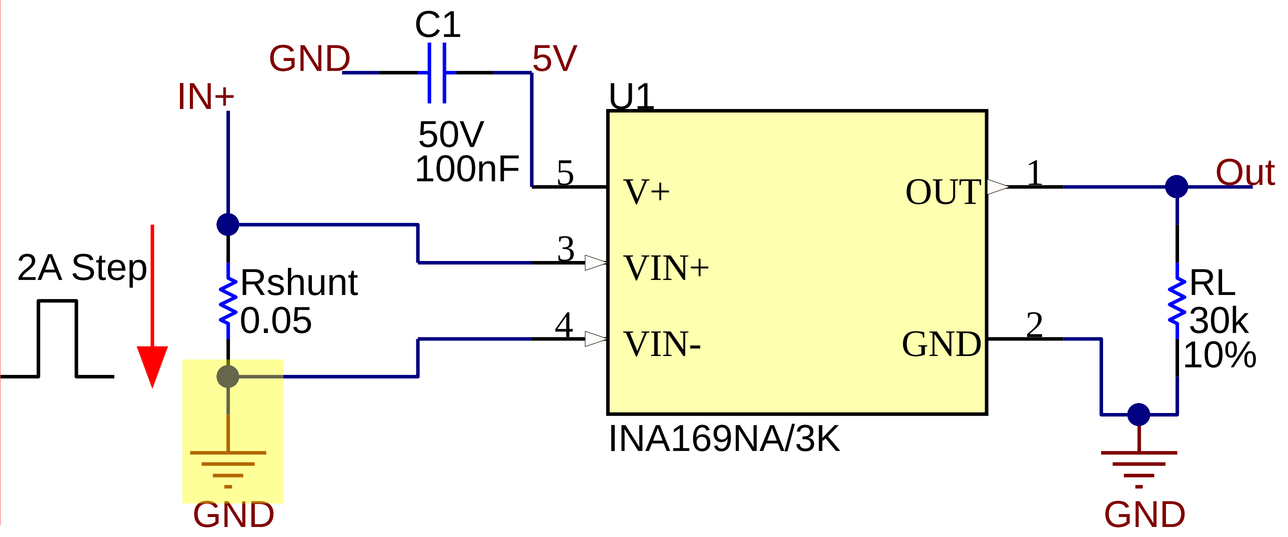


Debugging a Current Shunt Monitor – Overlooking Device Specs – Quiz

3. When applying a step response to the INA169, a relatively small output is seen on the output given that the output is expected to be $I_{Shunt}R_{Shunt}R_L$ /1kΩ. With the given details, what is likely the issue?

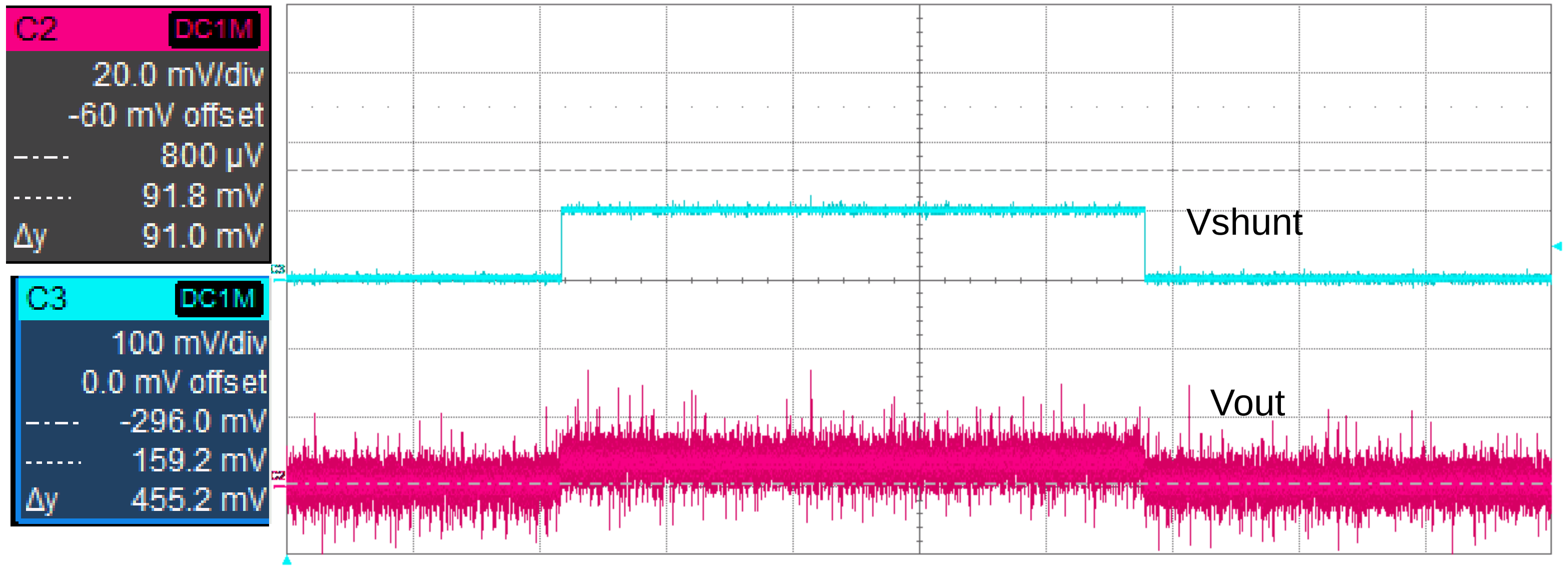
   a) A defective part
   b) Supply voltage is too low
   c) The common mode is outside of the recommended range
   d) Supply voltage is too high
   e) The current is too low.

The Vout appears to step up less than 20mV when we might expect it to be 3V. While it could be a defective part, we should not automatically assume that until we have ruled out all other sources of error. Supply is 5V, which is within spec. While an input bias current is not provided, 2A is not a small value for a standard current shunt monitor. The one obvious spec that is violated here is the common mode voltage, with the VIN- pin tethered to GND.



1 Features

- Complete Unipolar High-Side Current Measurement Circuit
- Wide Supply and Common-Mode Range
- INA139: 2.7 V to 40 V
- INA169: 2.7 V to 60 V
- Independent Supply and Input Common-Mode Voltages
- Single Resistor Gain Set
- Low Quiescent Current: 60 μA (Typical)
- 5-Pin, SOT-23 Packages



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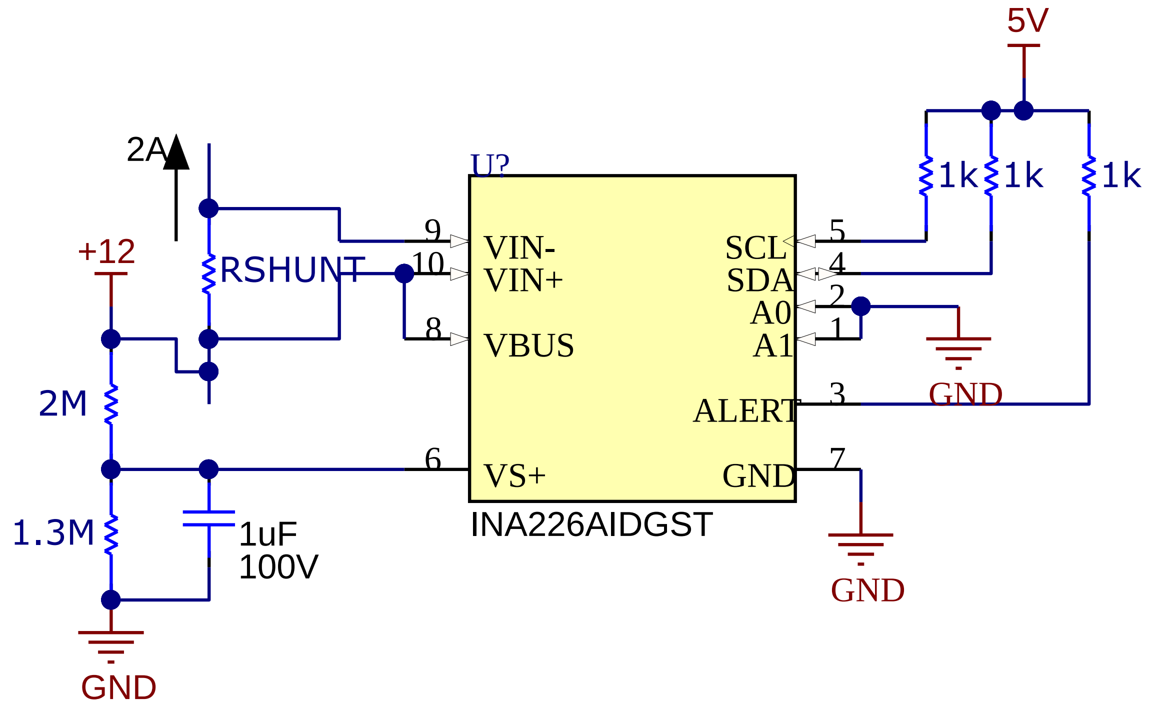
4. The device below displays an erroneous shunt voltage value .47s after power up. Each power-up leads to a different initial incorrect measurement. Default configuration register values are used. What might be the issue?

   a) Open GND
   b) I2C resistor values
   c) Supply voltage
   d) Configuration Register Setting

POINTER ADDRESS	REGISTER NAME	FUNCTION	POWER-ON RESET		TYPE (1)
HEX			BINARY	HEX	
00h	Configuration Register	All-register reset, shunt voltage and bus voltage ADC conversion times and averaging, operating mode.	01000001 00100111	4127	R/$\overline{W}$

1 Features

- Senses Bus Voltages From 0 V to 36 V
- High-Side or Low-Side Sensing
- Reports Current, Voltage, and Power
- High Accuracy:
  – 0.1% Gain Error (Max)
  – 10 µV Offset (Max)
- Configurable Averaging Options
- 16 Programmable Addresses
- Operates from 2.7-V to 5.5-V Power Supply
- 10-Pin, DGS (VSSOP) Package



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One of the first details provided is the read back time. If we look at the at the VS+ pin, we can see that the is extremely large RC filter. The voltage divider formula indicates VS+ is being set to 12V*1.3MΩ/(2MΩ+1.3MΩ)=4.72V. If look at the RC charging formula, we might expect the capacitor will take some time to charge up. If we do a simple simulation of this divider filter input, we see that at 0.47s the supply would be 2.13V. This is below 2.7V. This suggests that while the device may be outputting a result, not all of the circuits may be operating in their proper region, thereby producing a garbage result.