Understanding Current Sensing Applications & How to Choose the Right Device

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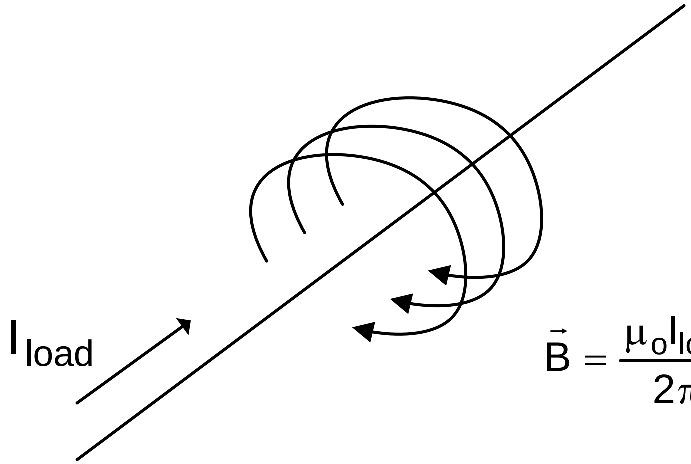
Outline & Presentation Goals

- Outline
  - Fundamentals
  - Devices
- Goals of this presentation
  - Select a current sensing topology (direct vs. indirect, high vs. low-side, etc.)
  - Select the appropriate device (op amp, difference amp, inst. amp, or CSM?)

Fundamentals

Indirect Sensing

- Based on Ampere's and Faraday's Laws
- Noninvasive
- Inherently isolated
- No power lost by the system
- Recommend
  - Very high currents (e.g. >100A)
  - Very high voltage
  - Very dynamic load currents
  - Isolation required



$$\vec{B} = \frac{\mu_o I_{load}}{2\pi r}$$

Indirect Sensing-Solutions

- Hall Effect Sensor
  - ADS1208, ADS1205, ADS7861, ADS8361, ADS8365
  - Application note SLAA286

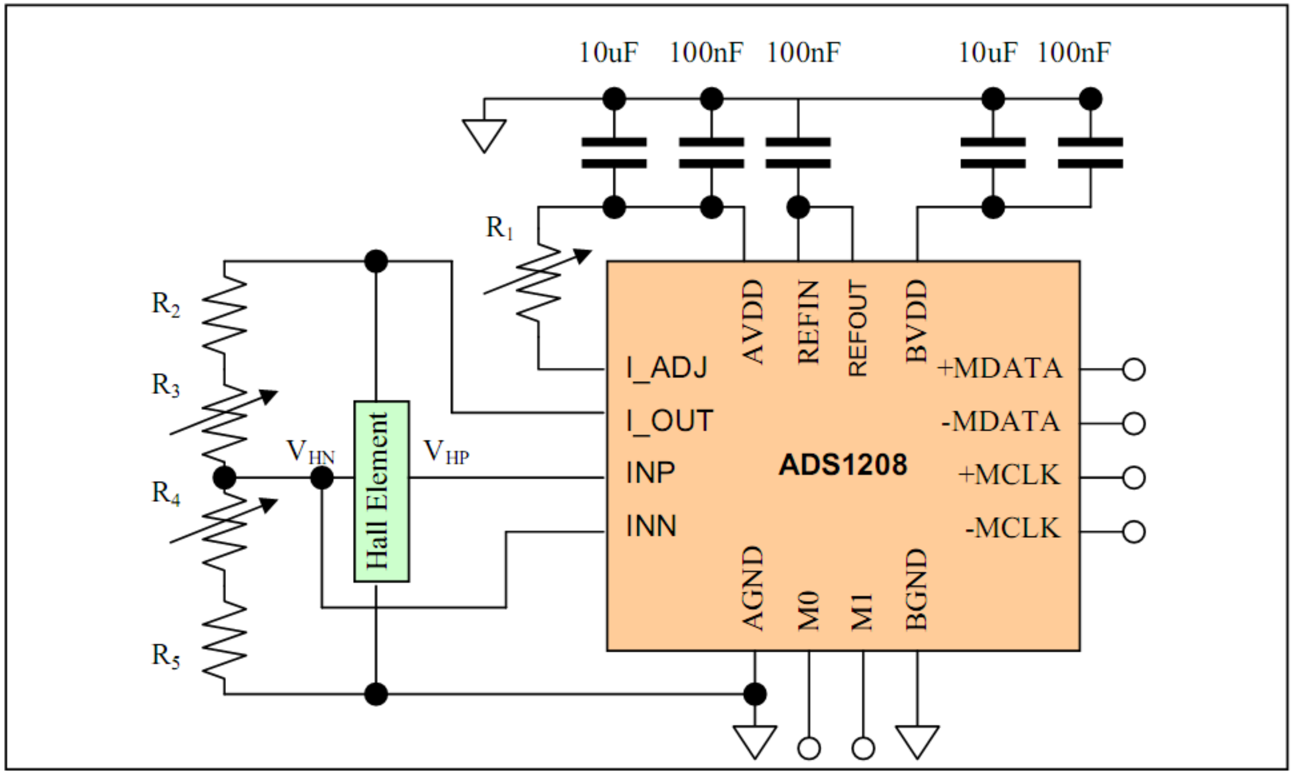
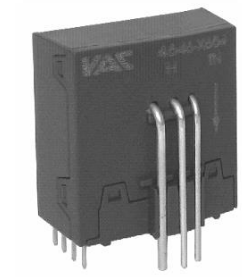


Figure 3: Hall module using the ADS1208

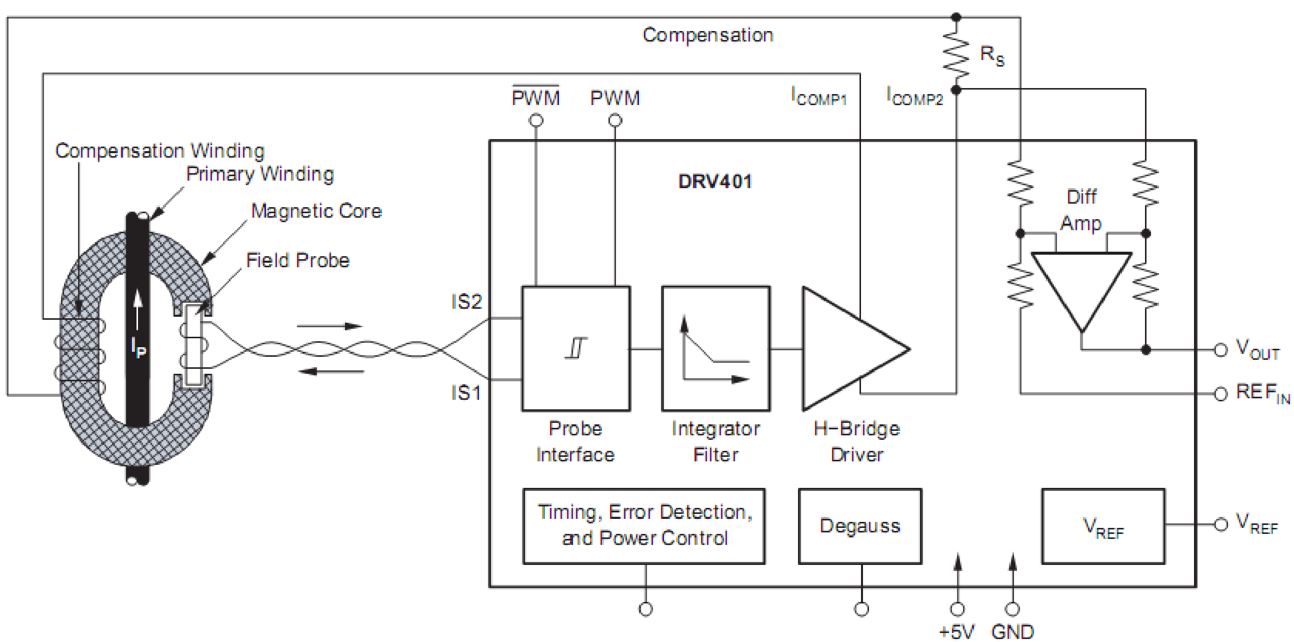
Indirect Sensing-Solutions

Type
T60404M-4645-X600
T60404M-4645-X601

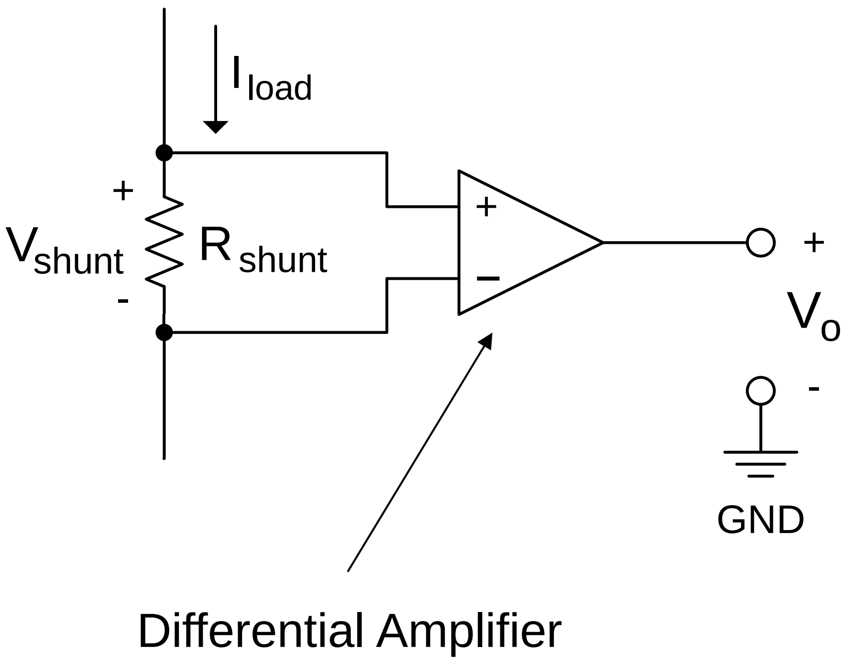


- VAC Sensor
  - DRV401 is a custom solution for VAC Sensors
  - Combine with SAR ADC (e.g. ADS8509)
  - Less sensitive to temperature drift and initial offset than Hall sensor solutions

Patents Pending.



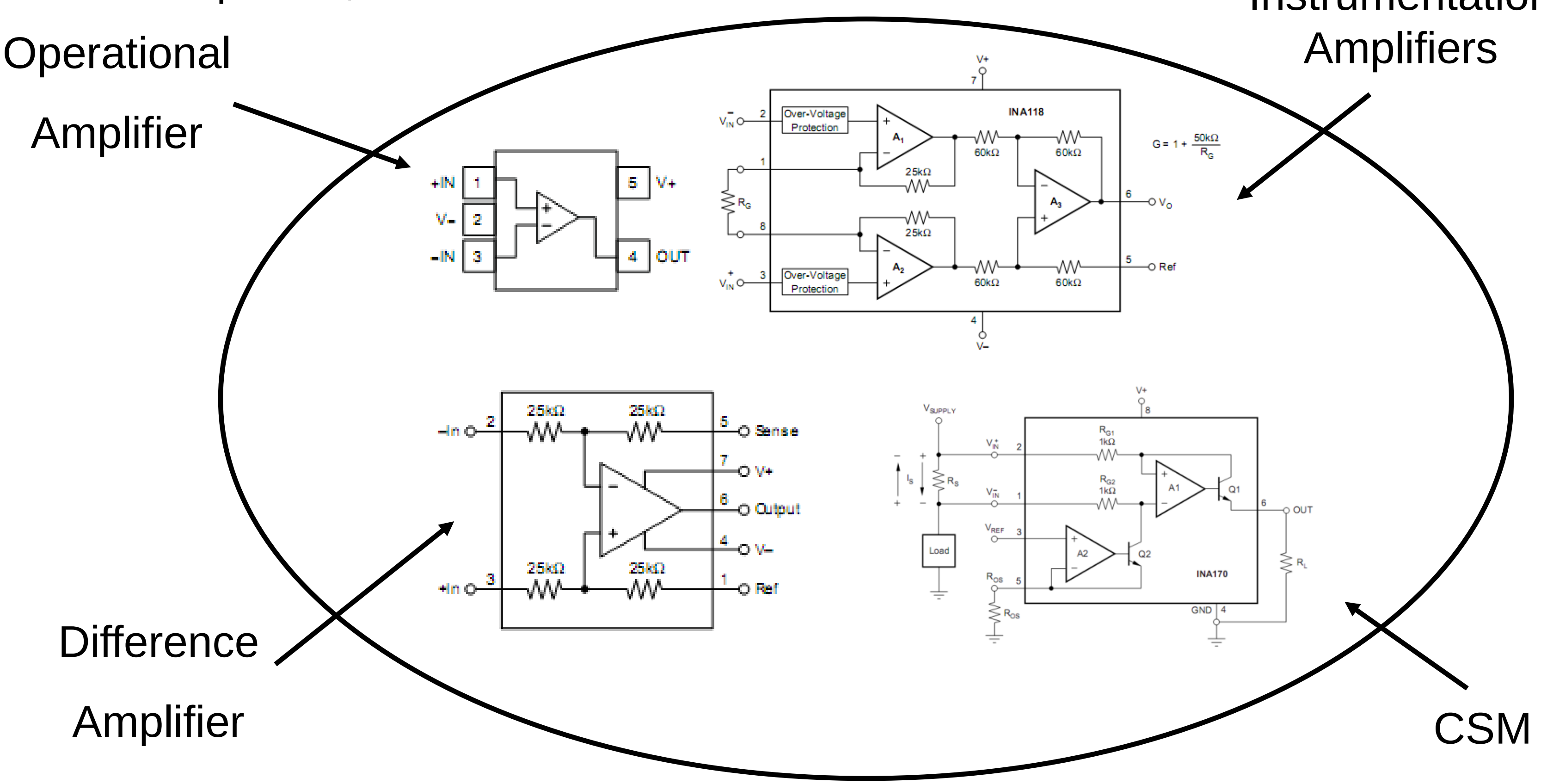
Direct Sensing



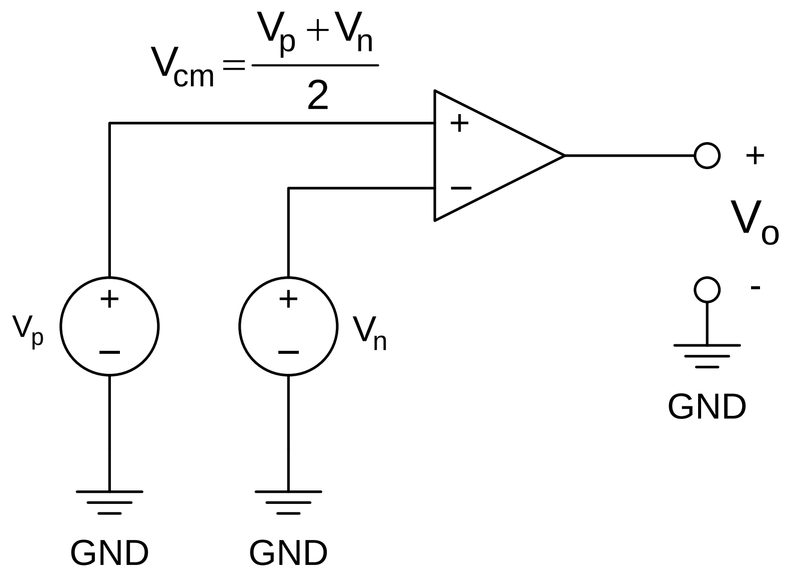
- Based on Ohm's Law
- Shunt resistor in series with load
- Invasive
- Power dissipated by Rshunt
- Sensing circuit not isolated from system load
- Recommend
  - Smaller currents (<100A)
  - System can tolerate power loss
  - Low voltage
  - Load current not very dynamic
  - Isolation not required (though it can be accomplished)

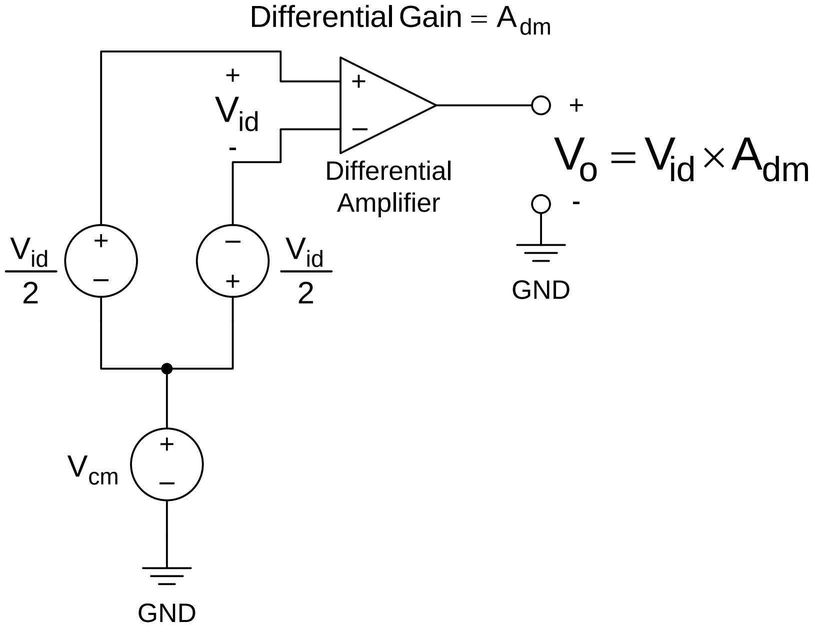
Differential Input Amplifier

- Differential input amplifiers are devices/circuits that can input and amplify differential signals while suppressing common-mode signals
  - This includes operational amplifiers, instrumentation amplifiers, difference amplifiers, and current-shunt monitors



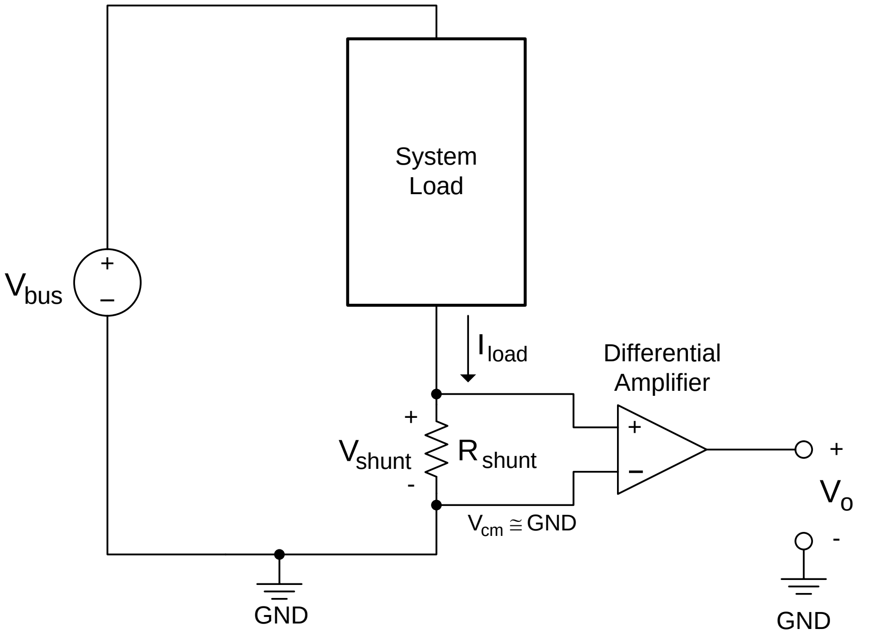
Common-Mode Voltage



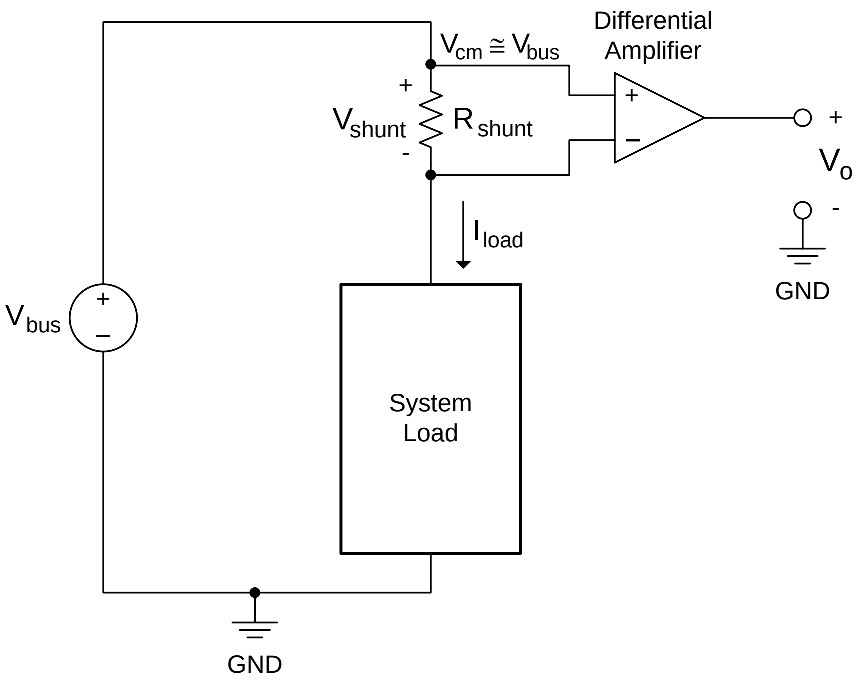


Low-Side Sensing

- Shunt resistor placed between the system load and ground
- Pros
  - Vcm≈0V
  - Straightforward
  - Inexpensive (may use an op amp)
- Cons
  - Can't detect load shorts to ground
  - Single-ended measurement (stay tuned)
  - System GND is now Iload*Rshunt



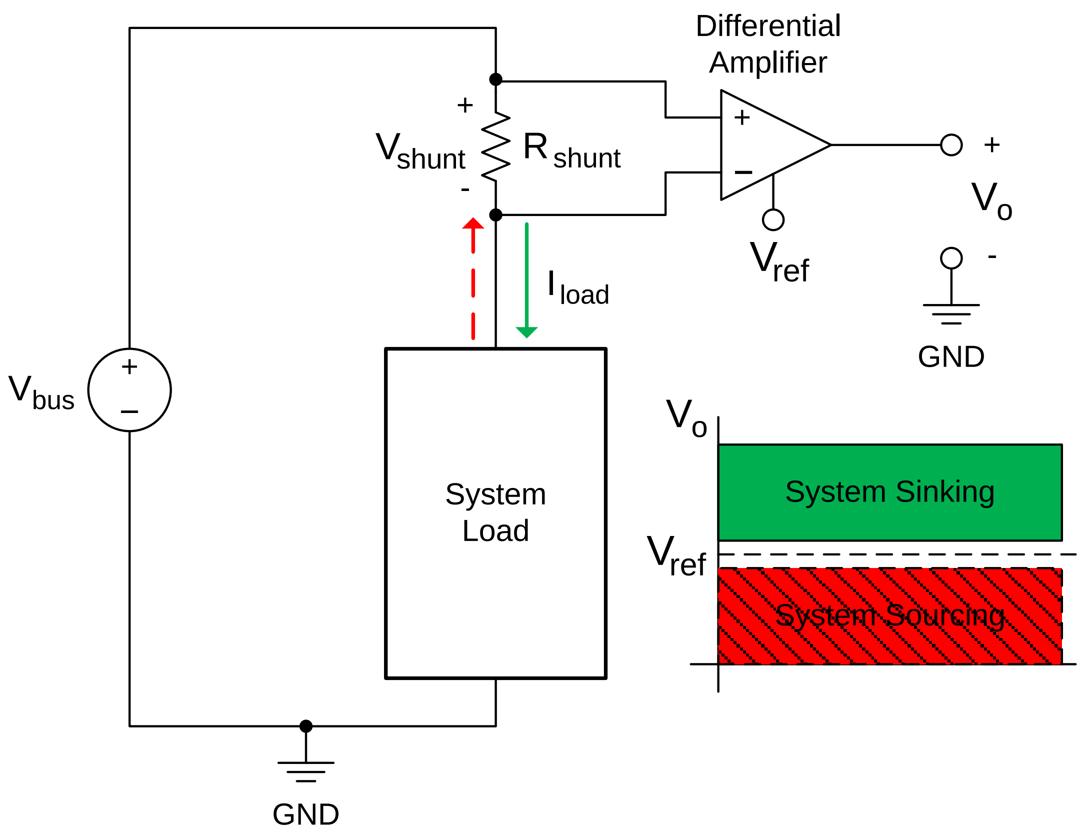
High-Side Sensing



- Shunt resistor placed between supply (Vbus) and system load
  - Pros
    - Can detect load shorts to ground
    - Monitors current directly from source
  - Cons
    - Vcm≈Vbus

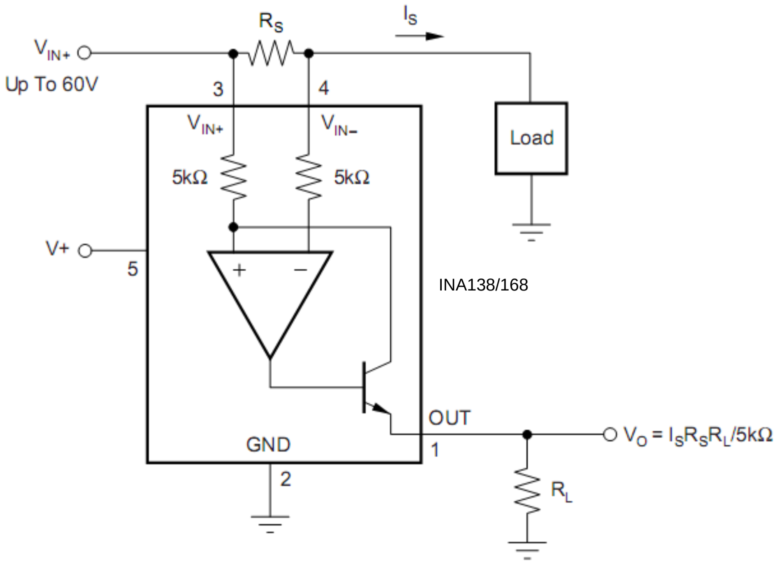
Directionality

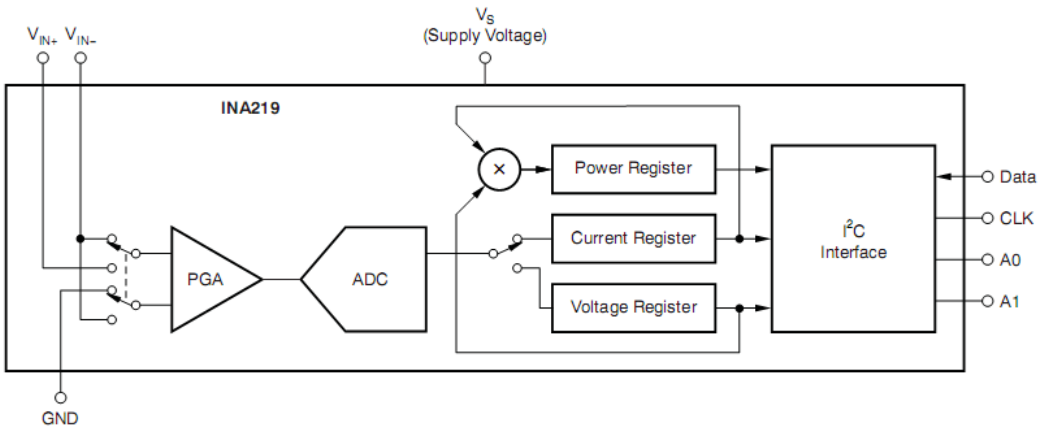
- Application may require sensing current in both directions

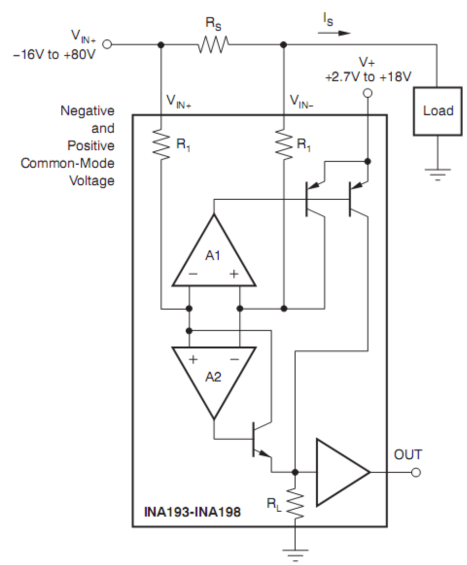


Output

- Op amps, difference amplifiers, and instrumentation amplifiers have voltage outputs
- Current shunt monitors can also have current-output and digital-output



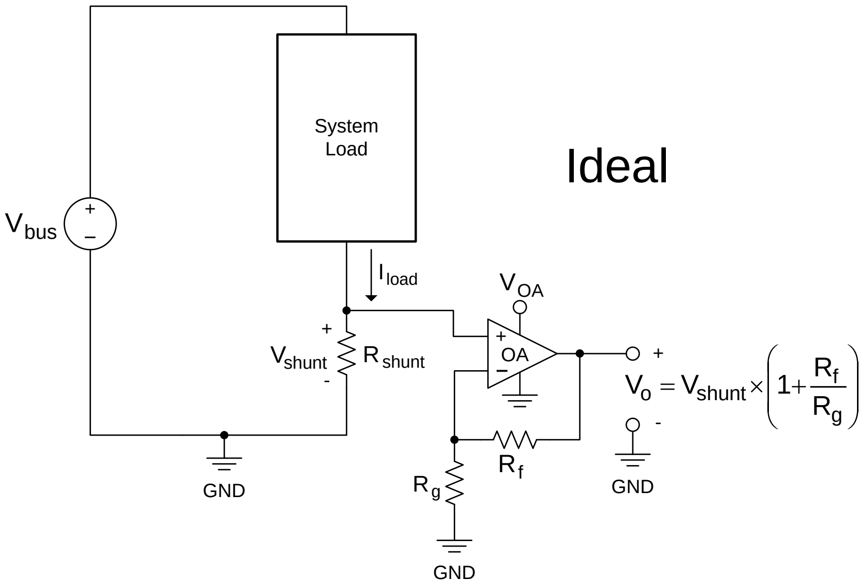




Devices

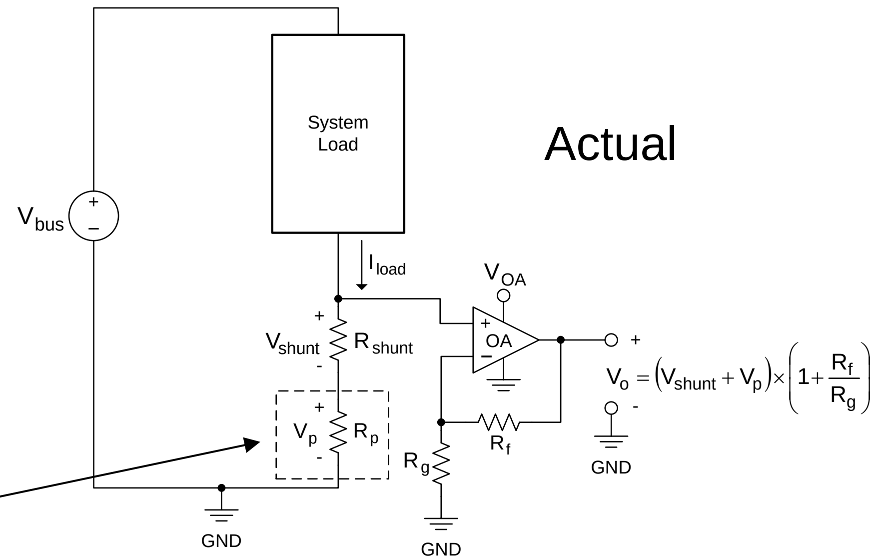
Op Amp-Low Side Only

Ideal



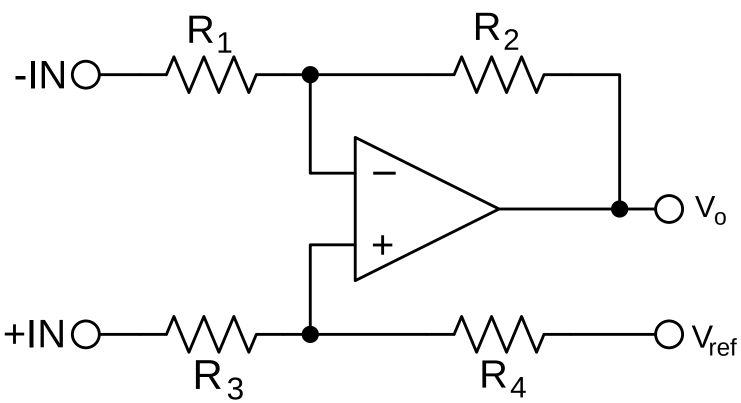
- Very large open-loop gain
- Must have feedback, so the input will be single-ended
- Therefore only useful on low-side where Vcm≈GND
- Beware of PCB layout parasitics

Actual

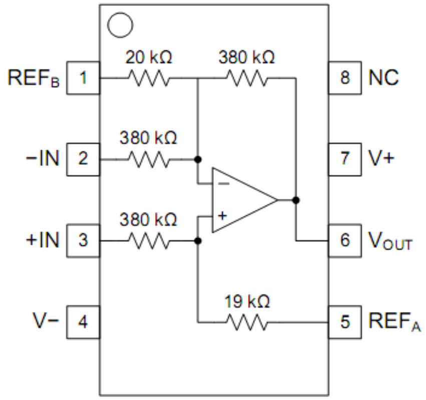


Parasitic impedance to ground introduces error

Difference Amplifier



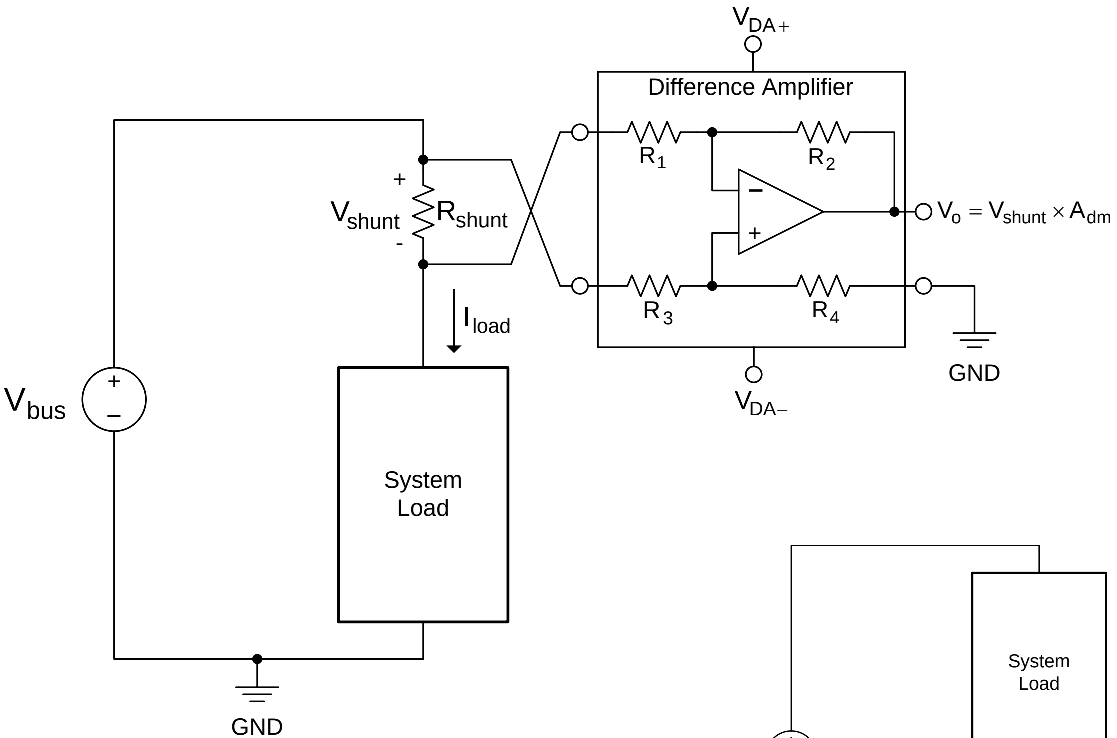
INA149

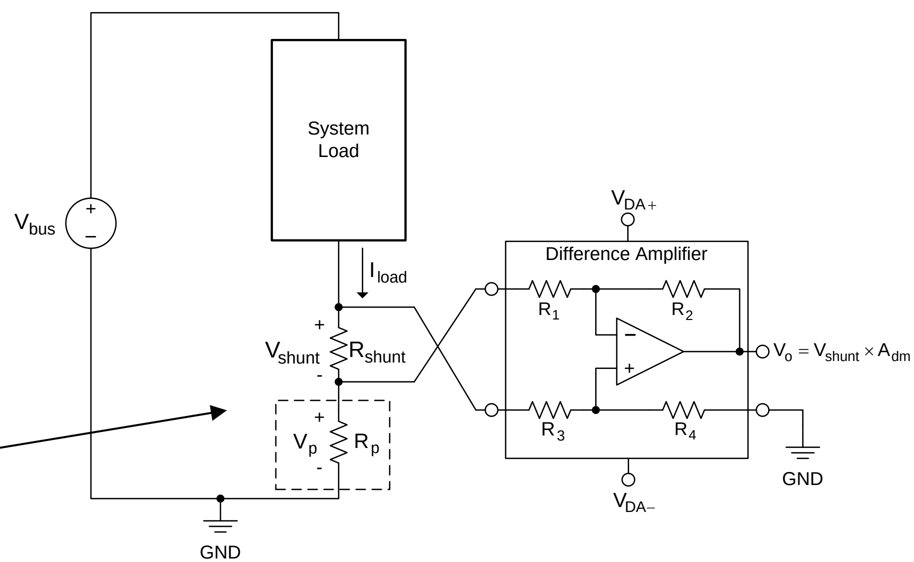


- Can be used for either high or low-side current sensing
- Can tolerate very large common-mode voltages (e.g. INA149 Vcm=±275V!)
- This is due to large resistive divider on input pins
- However this resistive network loads the system
- Ensure system impedance is significantly smaller than DA input impedances

INPUT			
Impedance	Differential	800	kΩ
	Common-mode	200	kΩ

Difference Amplifier

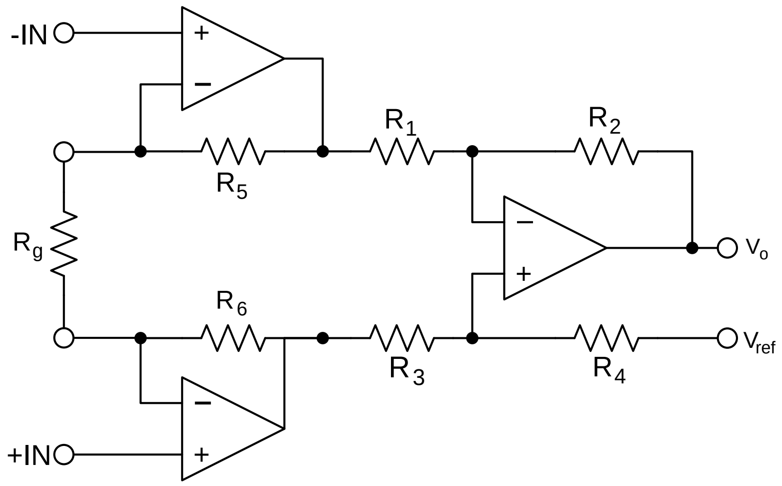




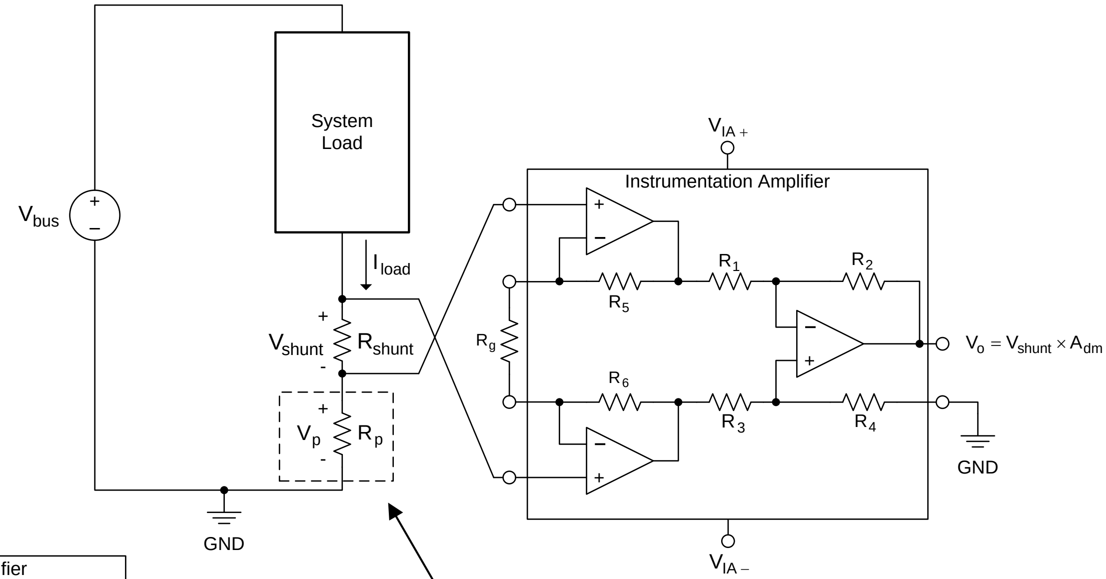
Solves PCB parasitic issue

Instrumentation Amplifier

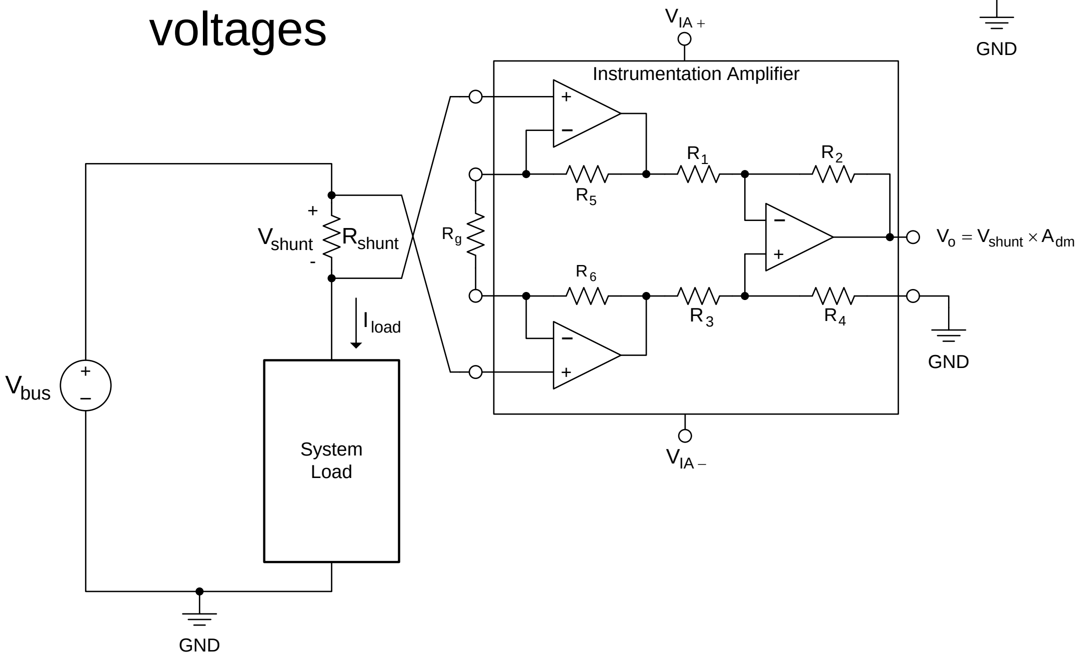
- A three op amp IA is made of a DA with buffered inputs
- Pros
  - Large input impedance
  - Change gain with external resistor
- Cons
  - Common-mode voltage must remain within supply voltage
- Usually used for low-side sensing, but can be used for high-side depending on common-mode voltage



Instrumentation Amplifier

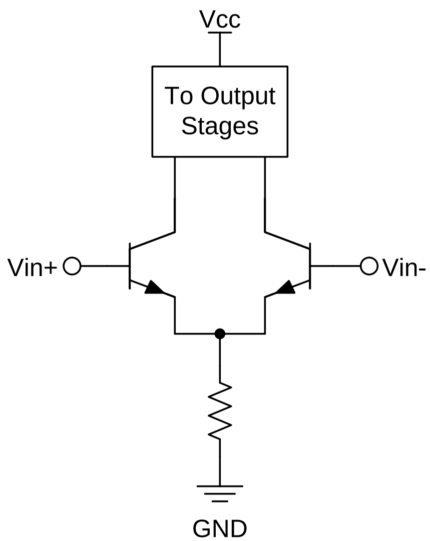


Vbus must be within Vcm range given IA supply voltages



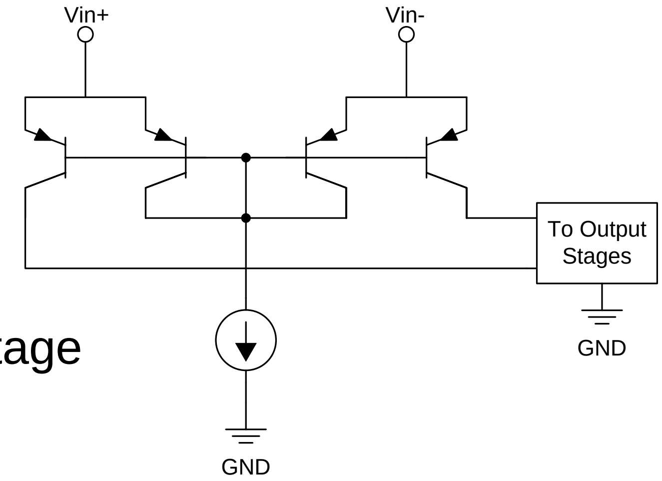
Differential measurement solves PCB parasitic issue

Current Shunt Monitors



Typical Op Amp Input Stage

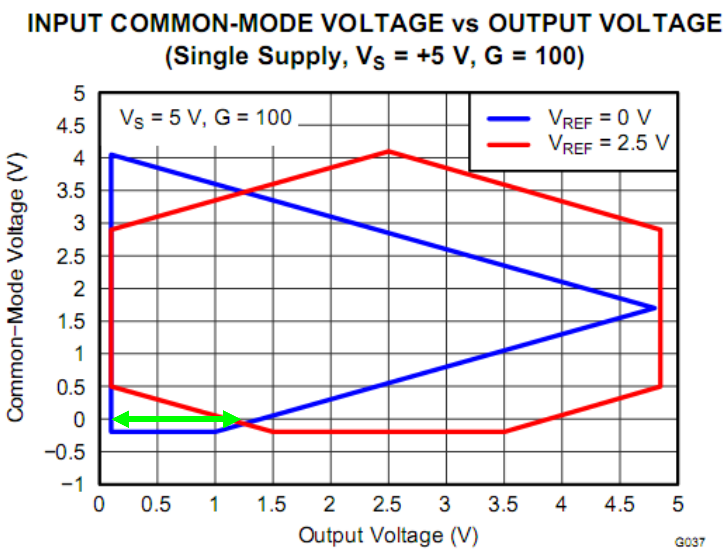
- Unique input stage topologies (e.g. common-base)
- This allows for Vcm values outside of supply voltages AND very large input impedances
- But, maximum Vcm value is currently 80V

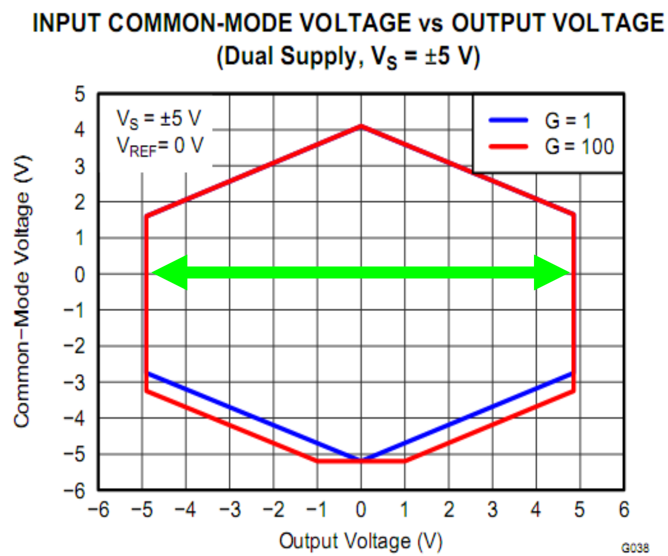


Example CSM Input Stage

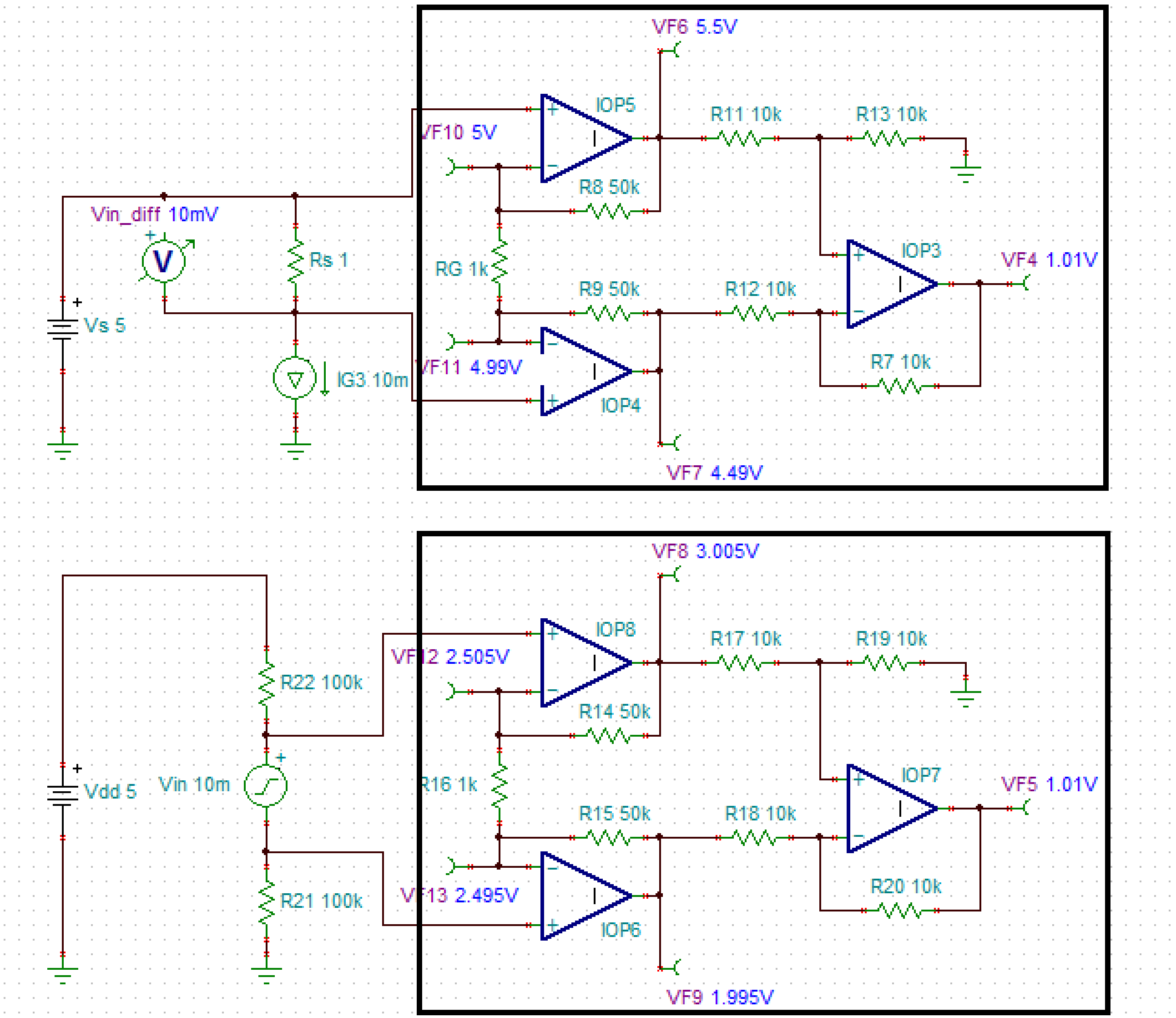
Input and Output Voltage Range

- Always ensure that desired input and output voltage ranges are within datasheet specifications
- Instrumentation amplifiers can be tricky
- For example, can we effectively use the INA826 for a low-side current measurement (Vcm≈0V)?

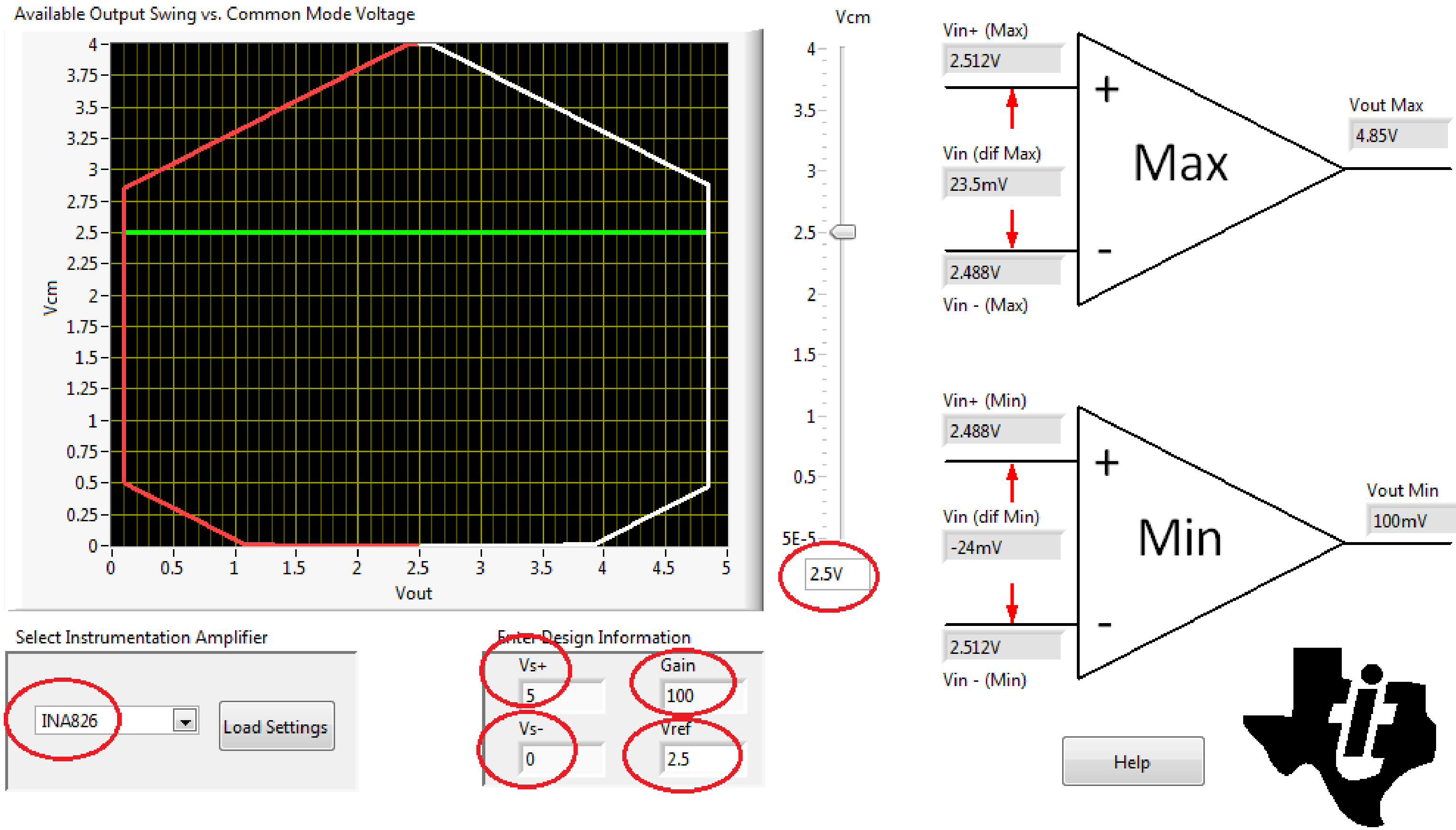




Reasons Behind Input & Output Voltage Limitations



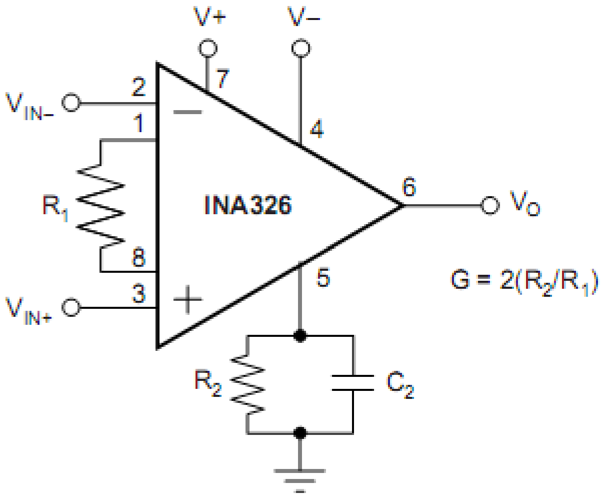
Instrumentation Amplifier Output Swing vs Common-Mode Voltage



- http://www.ti.com/tool/ina-cmv-calc

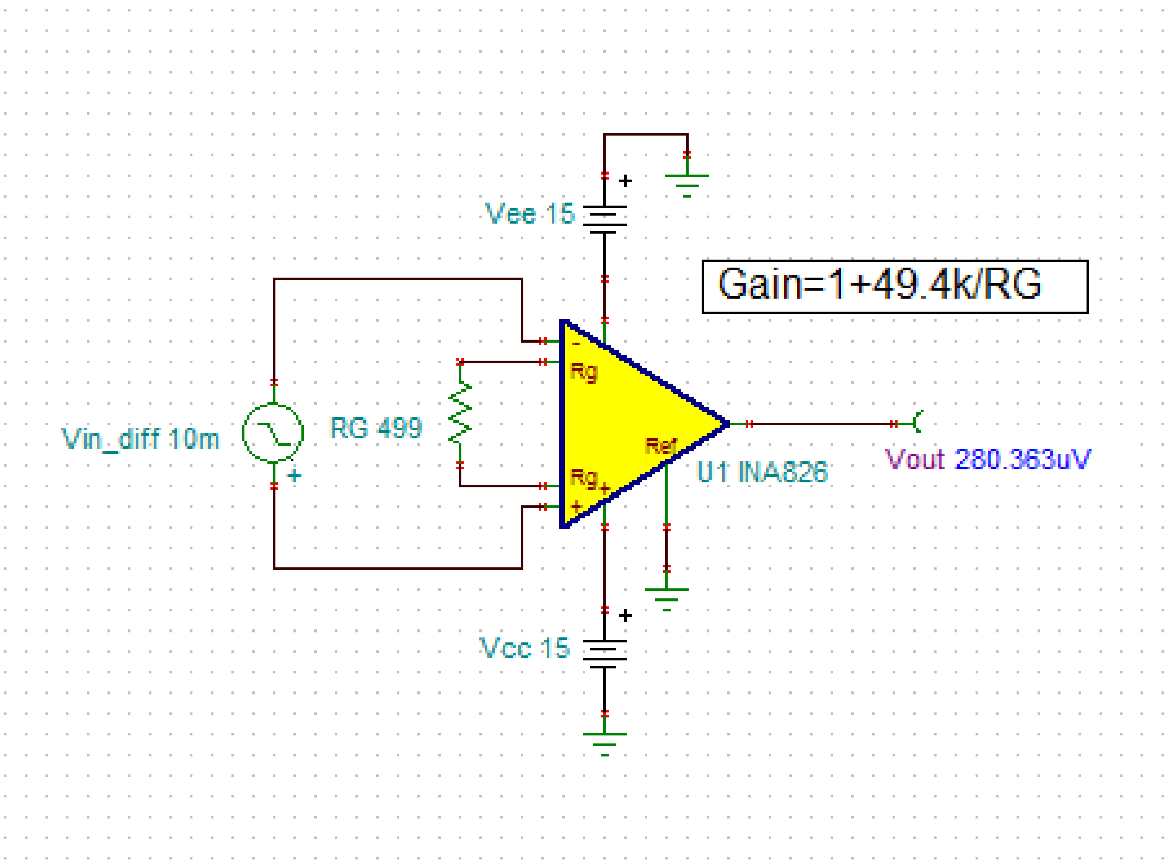
Unique Topologies

- Some instrumentation amplifiers have unique topologies that allow for RRIO on a single supply!
- INA326
  - Input voltage range (V-)-0.02 to (V+)+0.1
  - Output swings to within 75mV over temperature! (5mV typical)
  - Possible drawback: 1kHz BW

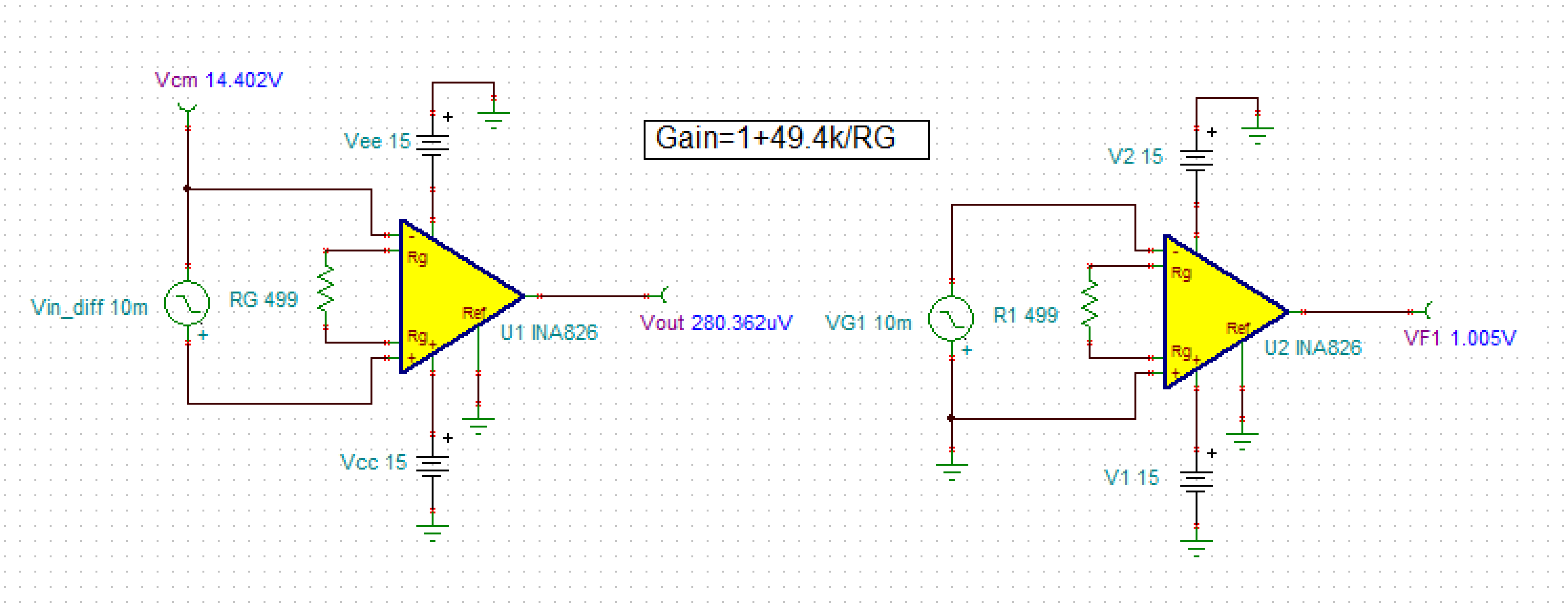


TEXAS INSTRUMENTS

Instrumentation Amplifier Most frequent Simulation Issue



Common-Mode Voltage Problems



Summary

	Vcm≈0V	0V<Vcm<Vdevice	Vcm>Vdevice
Small Load Current	Op Amp IA CSM	IA CSM	CSM
Large Load Current	Op Amp DA IA CSM	IA DA CSM	DA CSM

Questions?

Accuracy

Accuracy

- Definition
  - Worst case

$$\varsigma_{worst-case}(\%) = 100 - \sum_{1}^{n} e_n$$

  - Probable (Root-sum-square)

$$\varsigma_{RSS}(\%) = 100 - \sqrt{\sum_{1}^{n} {e_n}^2}$$

Error Sources

Description	Referred to
Input offset voltage (V_{OS})	Input
Offset voltage drift $\left(\frac{\Delta V_{OS}}{\Delta T}\right)$	Input
Offset voltage shift $\left(\frac{\Delta V_{OS}}{\Delta t}\right)$	Input
Gain error (%)	Output
Common-mode rejection (dB)	Input
Power supply rejection (dB)	Input
Input offset current (I_{OS})	Input
Shunt resistor tolerance (%)	Input

Input Offset Voltage (Vos)

- Definition
  - "The DC voltage that must be applied between the input terminals to force the quiescent DC output voltage to zero or some other level, if specified."
- Typically the largest source of error
- Error is calculated with respect to the ideal voltage across the shunt resistor (Vshunt)
- Example (INA170)
  - Vos(max)=1mV
  - Iload=5A (*nominal*)
  - Rshunt=1mΩ

How do we decrease this error?

- Decrease Vos(max)
- Increase Vshunt

$$e_{V_{os}} = \frac{V_{os(max)}}{V_{shunt}} \times 100 = \frac{V_{os(max)}}{I_{load} \times R_{shunt}} \times 100 = \frac{1mV}{5mV} \times 100 = 20\%$$

Common-mode Rejection Ratio (CMRR)

- Measure of a device's ability to reject common-mode signals
- Otherwise the common-mode signals can manifest themselves into differential signals which add to the error
- Specified one of two ways
  - Linear: µV/V
    - Worst case is the maximum value
  - Logarithmic: dB
    - Worst case is the minimum value
- Need the following to calculate error
  - Worst case specification
  - Common-mode test condition from datasheet (Vcm-pds)
  - System common-mode voltage (Vcm-sys)

CMRR Example

- Vcm-sys=50V
- Device: INA170
- Rshunt=1mΩ
- Iload=5A (nominal)
- First, convert 100dB to linear scale

ELECTRICAL CHARACTERISTICS

At $T_A = -40°C$ to $+85°C$, $V_S = 5V$, $V_{IN}^{+} = 12V$, $R_{OUT} = 25k\Omega$, unless otherwise noted.

PARAMETER	CONDITION	INA170EA MIN	INA170EA TYP	INA170EA MAX	UNITS
INPUT					
Full-Scale Sense (Input) Voltage	$V_{SENSE} = V_{IN}^{+} - V_{IN}^{-}$		100	500	mV
Common-Mode Input Range		+2.7		+60	V
Common-Mode Rejection	$V_{IN}^{+} = +2.7V$ to $+60V$, $V_{SENSE} = 50mV$	100	120		dB

How to we minimize this error?

$$CMRR_{INA170} = \frac{1}{10^{\frac{CMRR_{(dB)min}}{20}}} = \frac{1}{10^{\frac{100\,dB}{20}}} = 10\,\frac{\mu V}{V}$$

- Now calculate error contribution

$$e_{CMRR} = \frac{\left(\left|V_{cm-pds} - V_{cm-sys}\right|\right)\times CMRR_{INA170}}{V_{shunt}}\times 100 = \frac{\left(\left|12V - 50V\right|\right)\times 10\,\frac{\mu V}{V}}{5mV}\times 100 = 7.6\%$$

Power Supply Rejection Ratio (PSRR)

- Measure of the change in Vos created by a change in power supply voltage
- Calculation very similar to CMRR
- Need the following to calculate error
  - Worst case specification
  - Supply voltage test condition from datasheet (Vs-pds)
  - Device's supply voltage (Vs-sys)

PSRR Example

- Vs-sys=30V
- Device: INA170
- Rshunt=1mΩ
- Iload=5A (nominal)
- PSRR already specified in linear scale

ELECTRICAL CHARACTERISTICS

At $T_A = -40°C$ to $+85°C$, $V_S = 5V$, $V_{IN}^+ = 12V$, $R_{OUT} = 25k\Omega$, unless otherwise noted.

PARAMETER	CONDITION	INA170EA MIN	TYP	MAX	UNITS
INPUT					
Full-Scale Sense (Input) Voltage	$V_{SENSE} = V_{IN}^+ - V_{IN}^-$		100	500	mV
Common-Mode Input Range		+2.7		+60	V
Common-Mode Rejection	$V_{IN}^+ = +2.7V$ to $+60V$, $V_{SENSE} = 50mV$	100	120		dB
Offset Voltage[1] RTI			±0.2	±1	mV
vs Temperature	T_{MIN} to T_{MAX}		1		μV/°C
vs Power Supply	$V+ = +2.7V$ to $+60V$, $V_{SENSE} = 50mV$		0.1	10	μV/V

$$e_{PSRR} = \frac{\left(\left|V_{s-pds} - V_{s-sys}\right|\right) \times PSRR_{INA170}}{V_{shunt}} \times 100 = \frac{\left(\left|5V - 30V\right|\right) \times 10\,\frac{\mu V}{V}}{5mV} \times 100 = 5\%$$

- How do we reduce this error term?

Other Errors

- Gain error
  - Usually listed in datasheet as a percentage
- Shunt resistor tolerance
  - Usually given as a percentage. Beware of temperature drift, though.
- Vos drift
  - Usually listed in datasheet as μV/˚C
  - Multiply specification by maximum deviation from 25C
- Vos shift
  - Change in Vos due to time
  - Usually not specified. Most likely never guaranteed.
  - Rule of thumb: In 10 years, Vos may shift no more than the Vos(max) specification.
  - This is *in addition to* the device's initial Vos specification.

Putting It All Together

- Let's calculate the error of our example due to Vos, CMRR, and PSRR
- 20% error due to Vos (initial)
- 7.6% error due to CMRR
- 5% error due to PSRR

$$e_{total-worst-case}(\%) = \sum_{1}^{n} e_n = 20 + 7.6 + 5 = 32.6\%$$

$$e_{total-RSS}(\%) = \sqrt{\sum_{1}^{n} e_n{}^2} = \sqrt{20^2 + 7.6^2 + 5^2} = 21.97\%$$

Note: This is for the nominal load current. What if 2A<Iload<6A?

PCB Layout and Troubleshooting

Accuracy Revisited

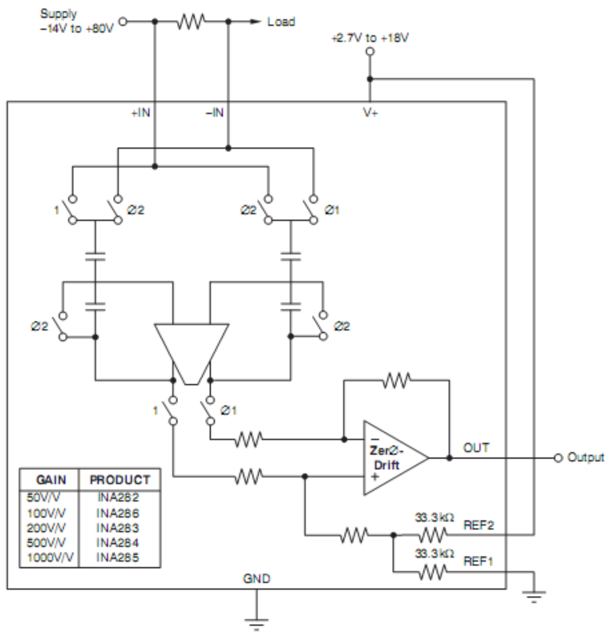
- System-Level Errors revisited
- Notice these are all *specifications*
- Are they under the control of the designer?
- New
  - Designer Control
  - Input Bias Current (Ib)
  - Vos-pcb
- Ib is defined as the average of the currents into the two input terminals with the output at the specified level.

Description	Referred to
Input offset voltage (V_{OS})	Input
Offset voltage drift $\left(\frac{\Delta V_{OS}}{\Delta T}\right)$	Input
Offset voltage shift $\left(\frac{\Delta V_{OS}}{\Delta t}\right)$	Input
Gain Error (%)	Output
Common-mode rejection (dB)	Input
Power supply rejection (dB)	Input
Input offset current (I_{OS})	Input
Shunt resistor tolerance (%)	Input

Example Design

- Requirements
  - Common-mode voltage (Vcm): 70V
  - Available supply for differential amplifier (Vs): 5V
  - Load current range: 5A<Iload<10A
  - Unidirectional
  - High accuracy
- Can't use an op amp due to Vcm
- Can't use an IA due to Vcm
- High accuracy->look at CSMs
- No mention of bandwidth->assume DC measurement

- INA282
  - -14V<Vcm<80V
  - Vos=70µV
  - 2.7V<Vs<18V
  - Bi-directional



Sizing the Shunt Resistor

- We need the following to size the shunt resistor
  - Load current range
  - Available supply voltage
- For this example
  - 5A<Iload<10A
  - Vs=5V
- Strategy
  - Obtain output voltage range from datasheet
  - Refer it back to the input by dividing by the device’s gain
  - Use load range minimum and maximum to find range of acceptable shunt resistor values

Sizing the Shunt Resistor

- Input and Output Range-INA282
  - Output Range: GND+40mV<Vout<Vs-0.4V
    - Since Vs=5V, 40mV<Vout<4.6V
  - Refer to input by dividing by gain (INA282 Gain=50V/V)
  - Input Range: 800µV<Vin<92mV

- Calculate maximum and minimum values for the shunt resistance

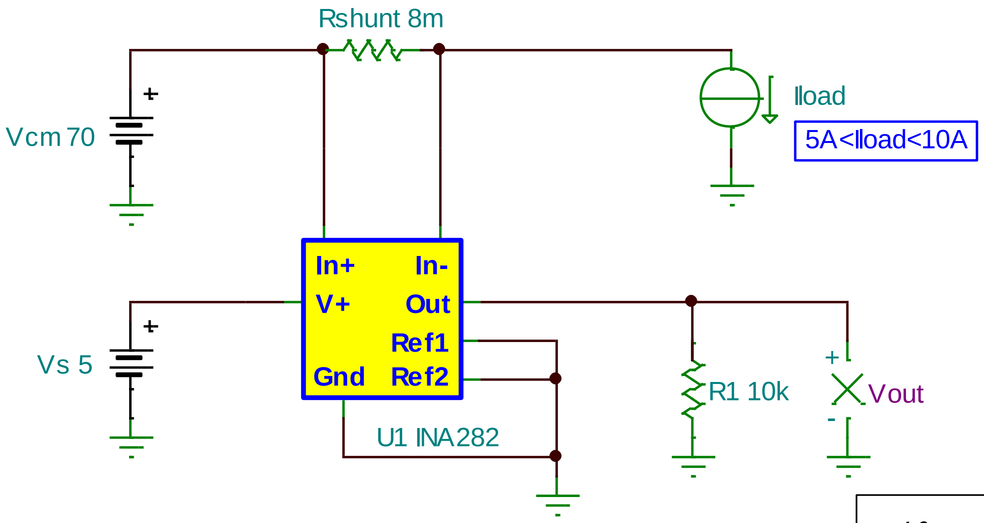
$$R_{shunt-max} = \frac{V_{in-max}}{I_{load-max}} = \frac{92mV}{10A} = 9.2m\Omega$$

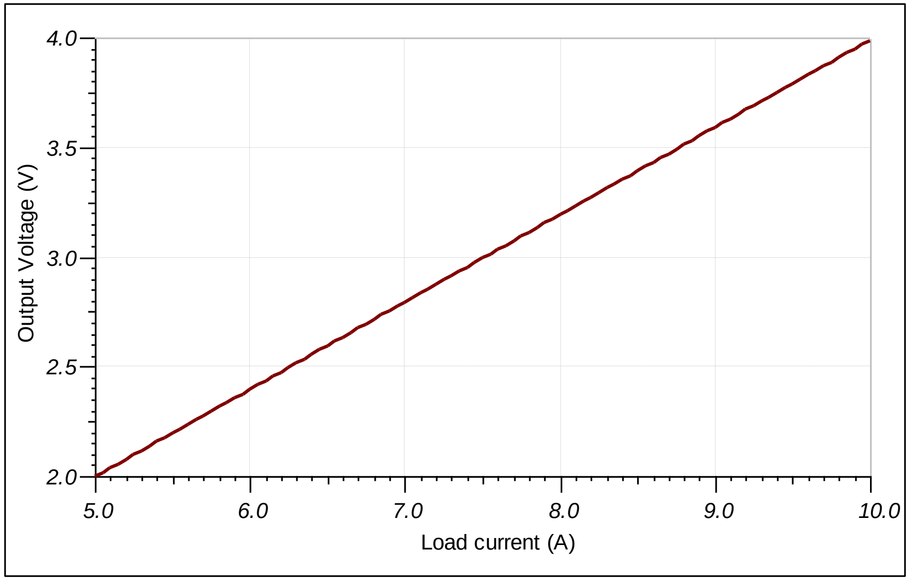
$$R_{shunt-min} = \frac{V_{in-min}}{I_{load-min}} = \frac{800\mu V}{5A} = 0.16m\Omega$$

- Note: Rshunt value is directly related to both power and accuracy

- So, use the largest Rshunt that your system can tolerate

Example Simulation



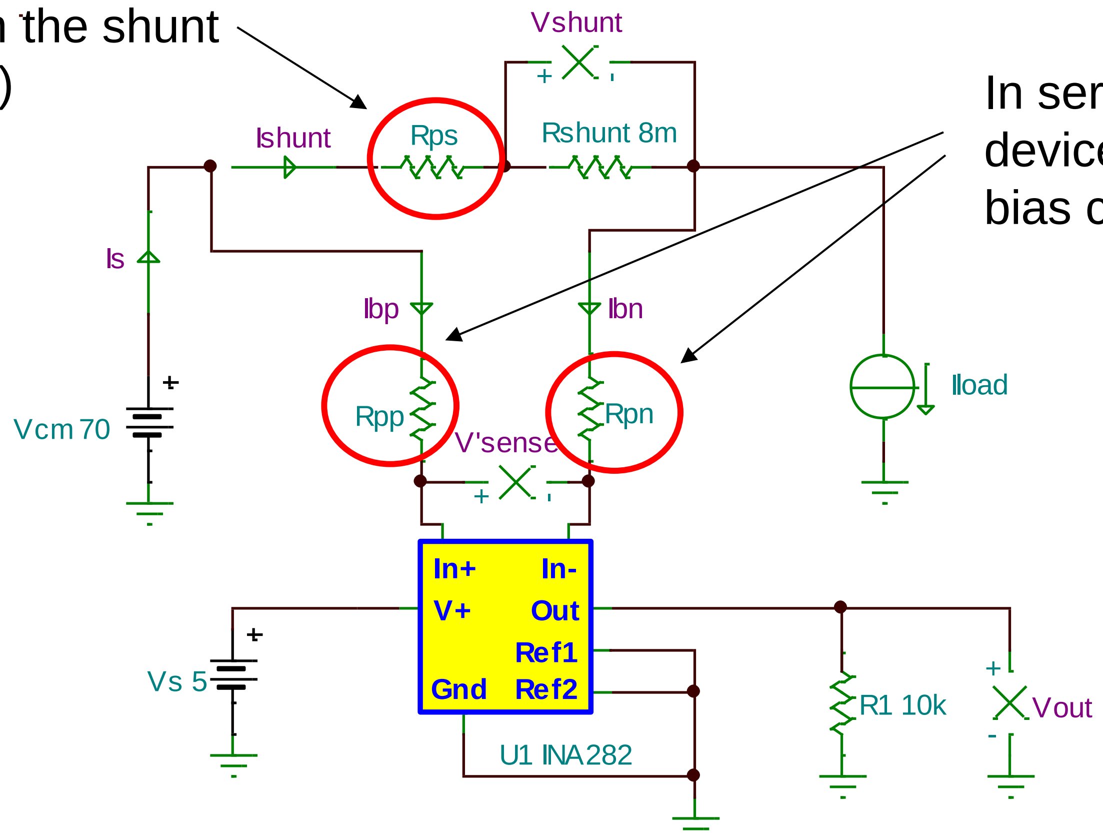


PCB Parasitics

- There are 3 parasitic resistances that can affect the accuracy

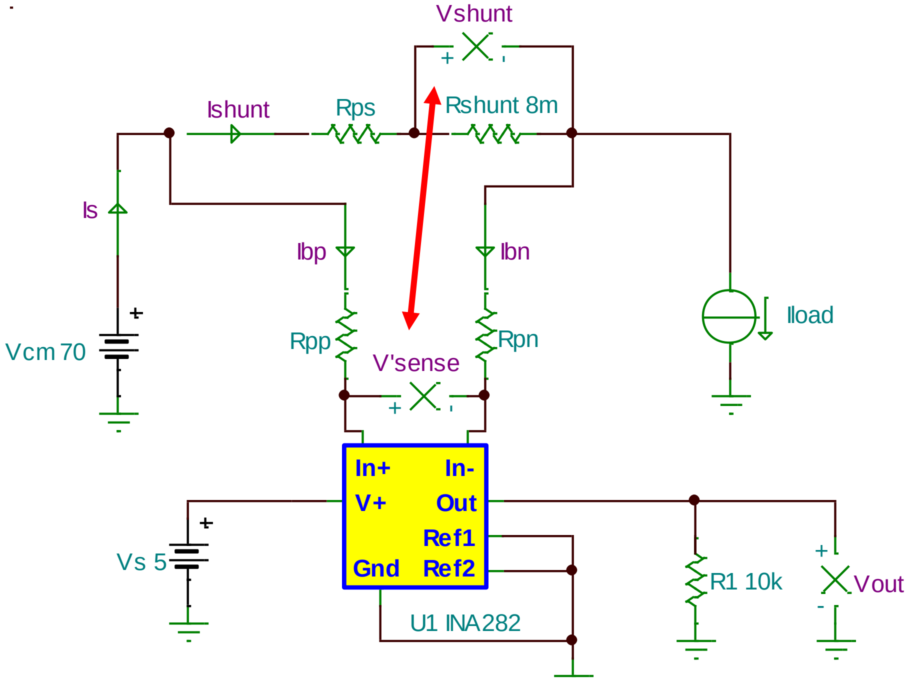
In series with the shunt (load current)

In series with the device inputs (input bias current)



PCB Parasitics

- Ideally Vshunt=Vsense
- Vsense is the voltage ***<u>at the pins</u>*** of the device
- However, the parasitics cause Vshunt≠Vsense, so we will rename the voltage at the pins to V'sense



$$V_{OS-PCB} = \left|V_{shunt} - V'_{sense}\right|$$

$$e_{PCB}(\%) = 100 \times \frac{V_{OS-PCB}}{V_{shunt}}$$

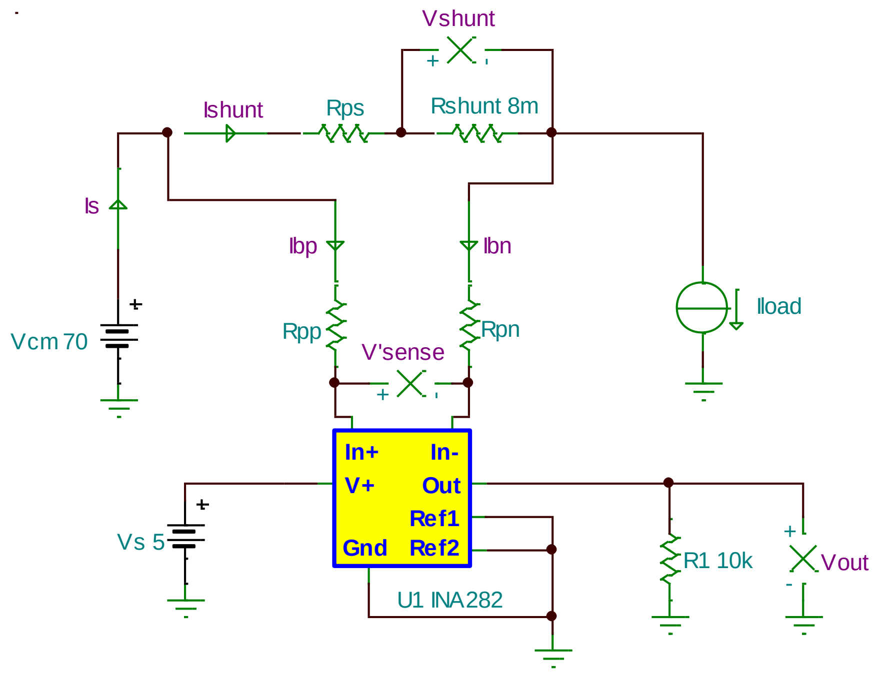
Ideal Shunt Voltage

PCB Parasitics

Input bias currents may or may not induce an error

- If we solve for V'sense we get

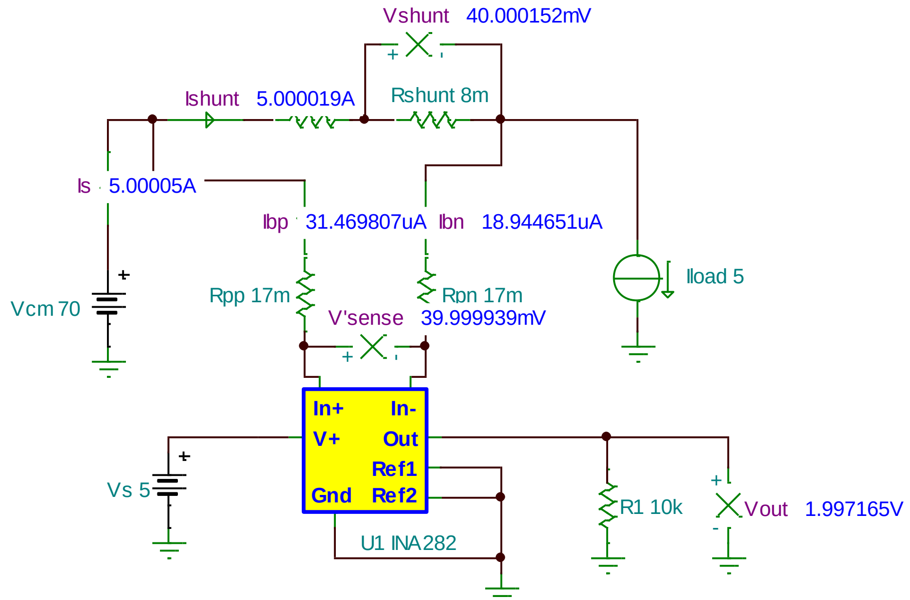
$$V'_{sense} = V_{shunt} + \left(I_{shunt} R_{ps}\right) + \left(\left(I_{bp} R_{pp} - I_{bn} R_{pn}\right)\right)$$



ANY parasitic resistance in series with the shunt resistor will induce an error

Balanced Rpn and Rpp Error

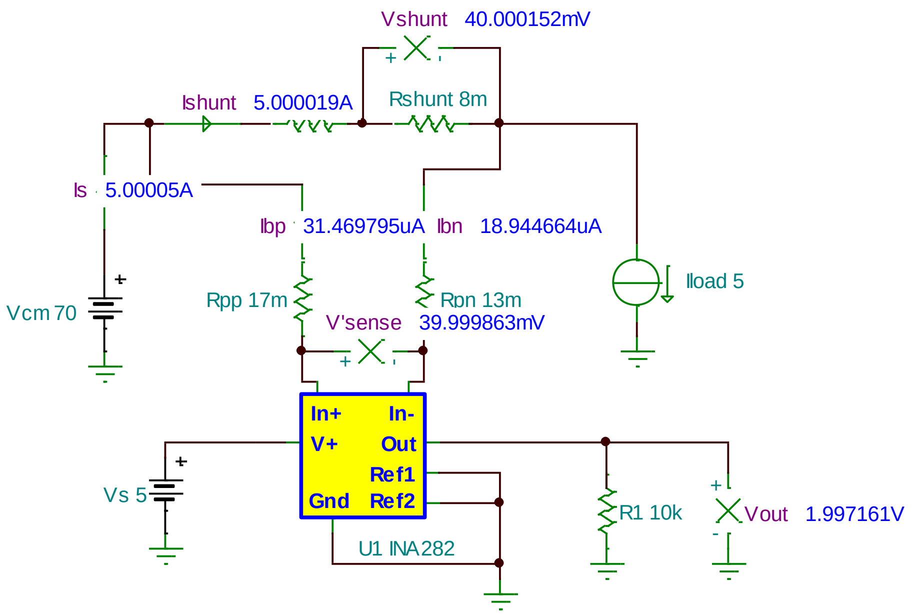
- One-ounce copper input traces of 350mils in length and 10mils wide have an impedance of approximately 17mΩ.



$$e_{PCB} = 100 \times \frac{V_{OS-PCB}}{V_{shunt}} = 100 \times \frac{\left|V_{shunt} - V'_{sense}\right|}{V_{shunt}} = 532.5\mu\%$$

Unbalanced Rpn and Rpp Error

- Assume Rpp=350mils and Rpn=275mils (13mΩ)



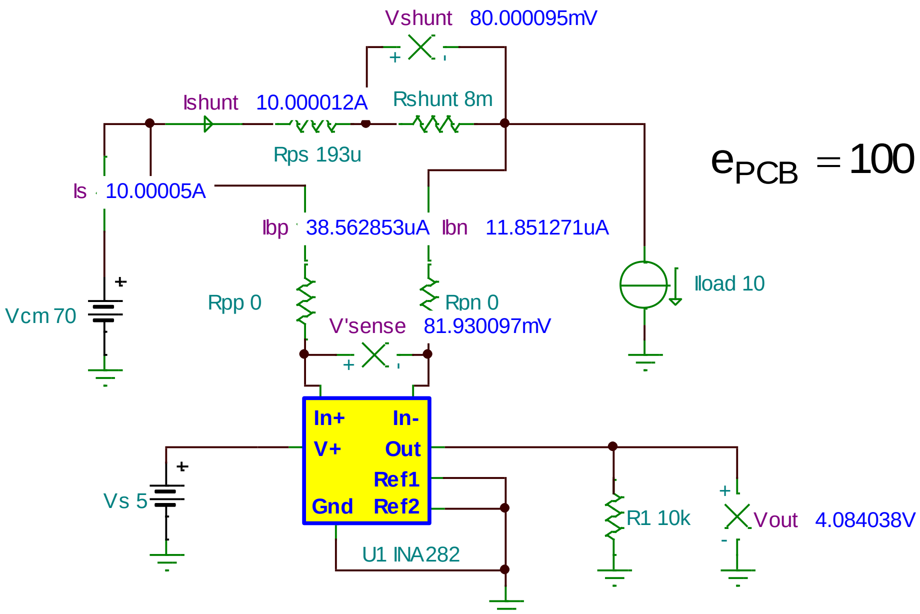
$$e_{PCB} = 100 \times \frac{V_{OS-PCB}}{V_{shunt}} = 100 \times \frac{\left|V_{shunt} - V'_{sense}\right|}{V_{shunt}} = 722.5\mu\%$$

Rpn and Rpp Error Observations

- These errors are generally not significant
- Placing the device and shunt on opposite sides of the board can exacerbate the error due to vias and temperature drift
- Attempting to size the input traces such that Ibp*Rpp=Ibn*Rpn is not recommended
  - Ib can vary part-to-part, wafer-to-wafer, and lot-to-lot.
  - It can also vary based on system parameters such as common-mode voltage and power supply
- PCB Layout Recommendations
  - Make the input traces as short as possible
  - Make the input traces as balanced as possible
  - Place the current sensing device and shunt on the same side of the PCB

Rps Error

- ANY resistance in series with the shunt will induce an error
- One-ounce copper trace of 10mils in length and 25mils wide has an impedance of approximately 193μΩ.
  - Recall that Rps is in the high-current path

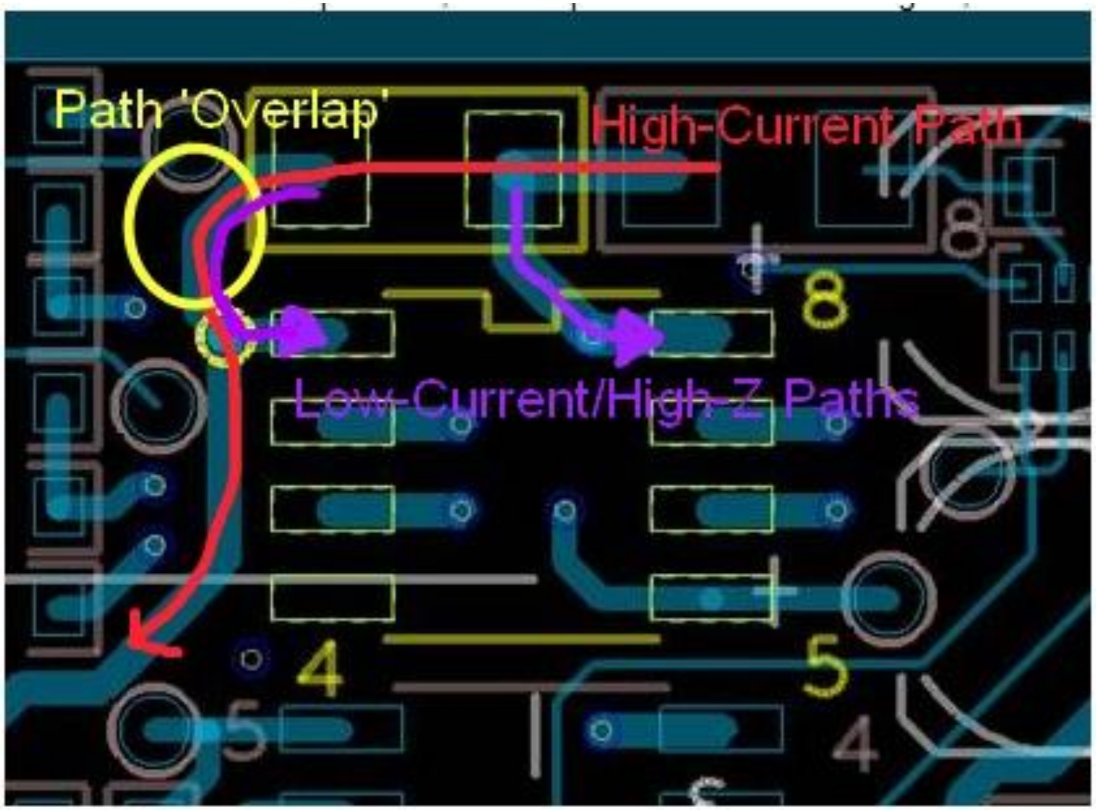


$$e_{PCB} = 100 \times \frac{V_{OS-PCB}}{V_{shunt}} = 100 \times \frac{|V_{shunt} - V'_{sense}|}{V_{shunt}} = \boxed{2.41\%}$$

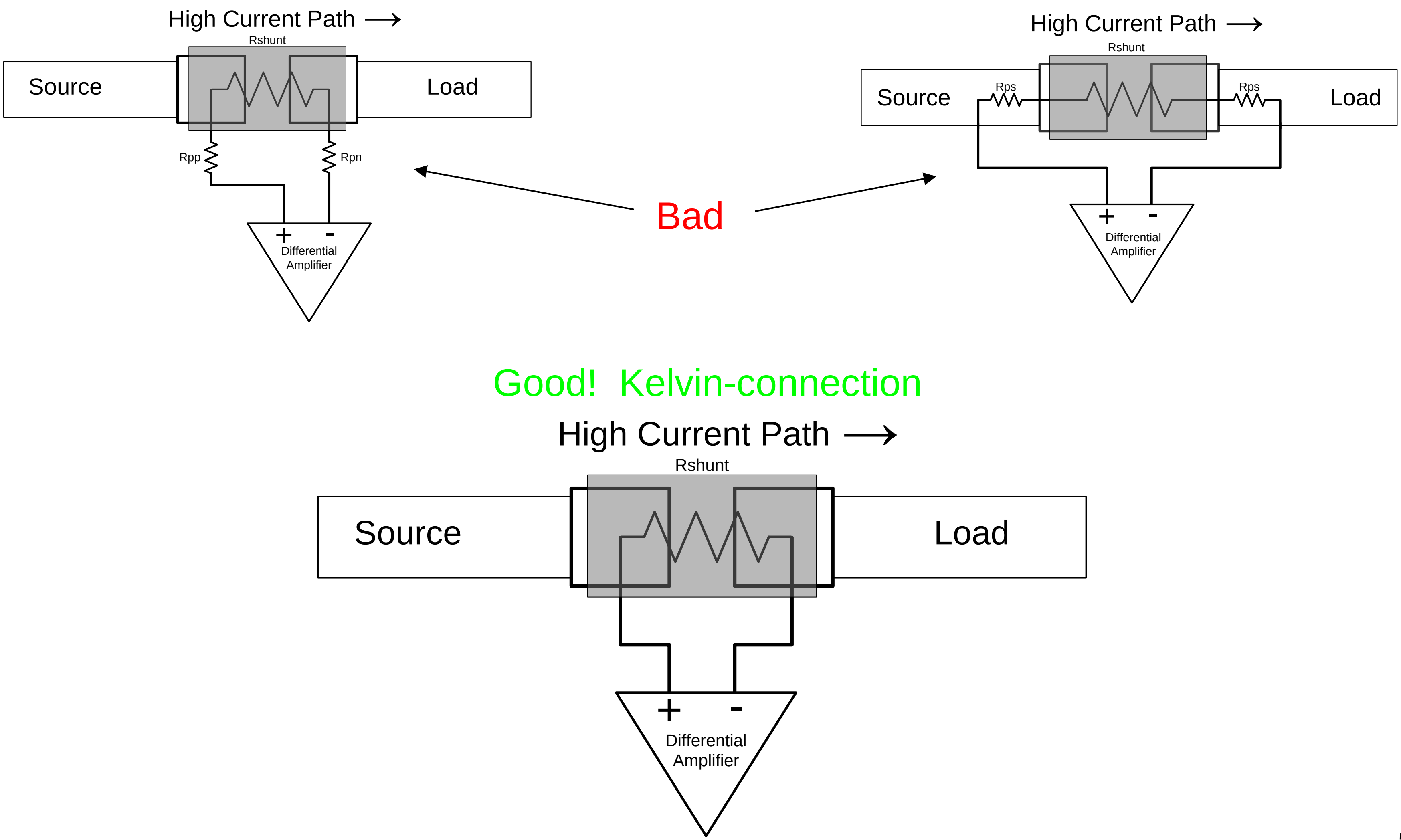
2.41% error due to 193μΩ!

How did we get resistance in series with Rshunt? Rshunt not Kelvin-connected!

Rps Error Example

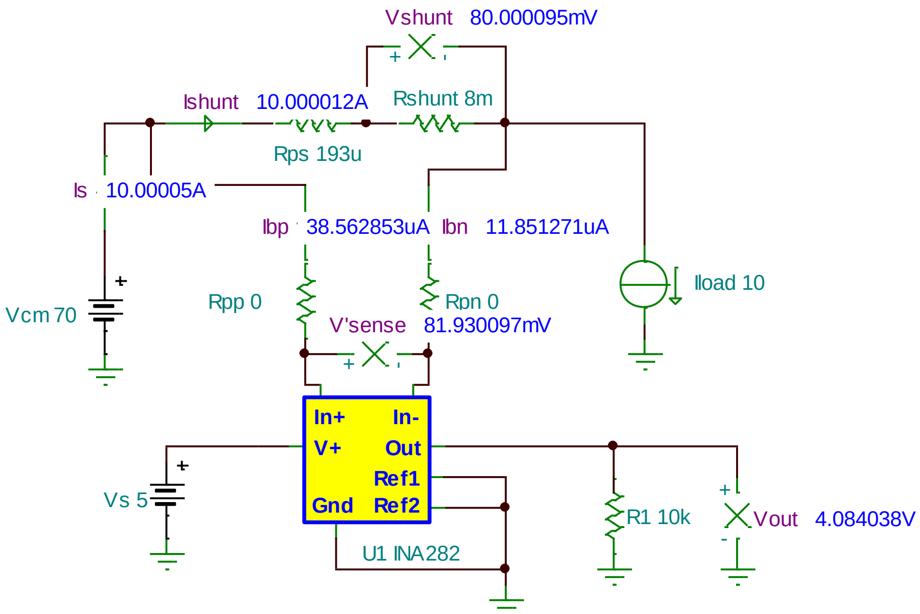


PCB Layout Summary



Rps Error

- Many engineers verify this circuit by comparing the output (4.084V) to the product of the shunt voltage (80mV) and the device’s gain (50V/V)
- This shows 84mV of error, which is unacceptable for the INA282.
- Conclusion: The device’s gain is incorrect…let’s do a failure analysis!



Rps Error

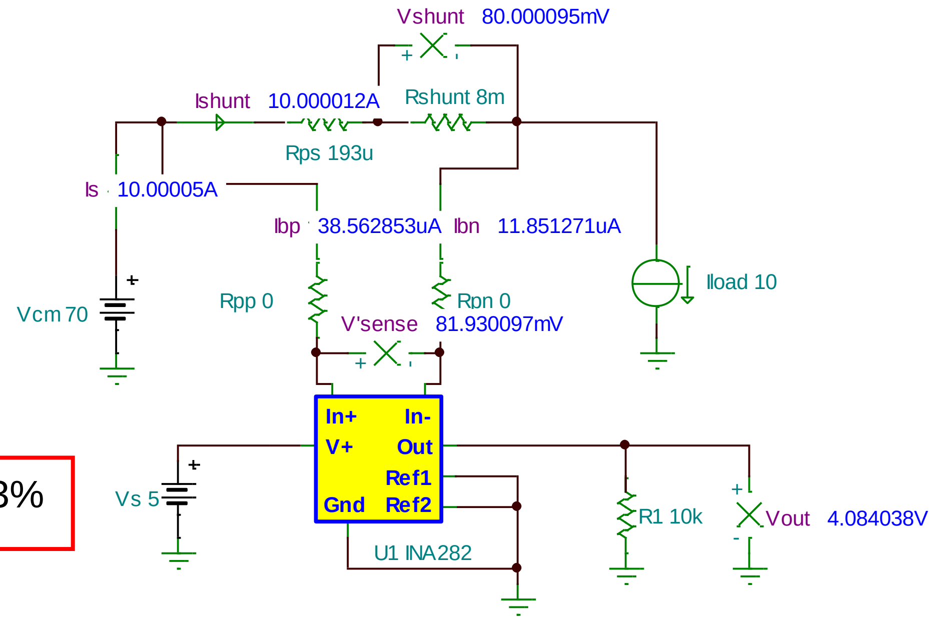
- Not so fast!
- To determine error introduced by the device you must use ***<u>V'sense</u>***

$$V_{out-ideal} = V'_{sense} \times Gain$$

$$e_{device}(\%) = 100 \times \frac{\left| V_{out-measured} - V_{out-ideal} \right|}{V_{out-ideal}}$$

$$e_{device}(\%) = 100 \times \frac{\left| 4.084\,V - \left(81.93mV \times 50\,\frac{V}{V} \right) \right|}{\left(81.93mV \times 50\,\frac{V}{V} \right)} = 0.3\%$$

Not the device…no FA required.



PCB Layout & Troubleshooting Summary

- Always ensure that the shunt resistor is Kelvin-connected
- Make the input traces as short as possible
- Make the input traces as balanced as possible
- Place the current sensing device and shunt on the same side of the PCB
- To determine device error, look at voltage across device pins (Vsense)
- Check to see if device is within specification for given application
  - Quickly calculate error referred to output due to Vos, CMRR, and PSRR

Questions?

Additional Reading

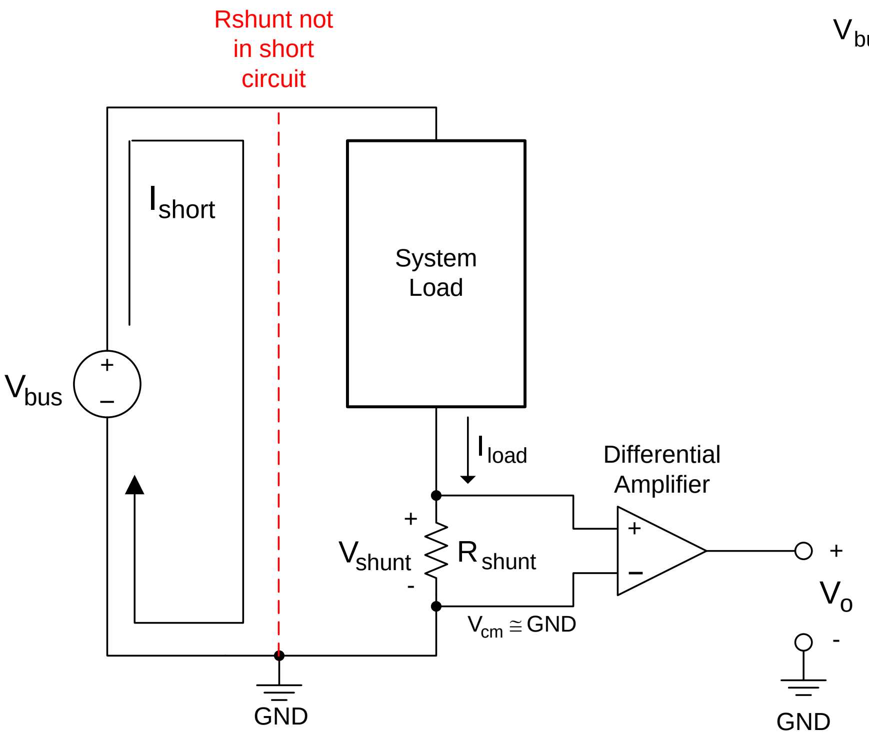
- Current Sensing Fundamentals
- Current Sensing Devices
- Current Sensing Accuracy
- Current Sensing Layout & Troubleshooting

Devices

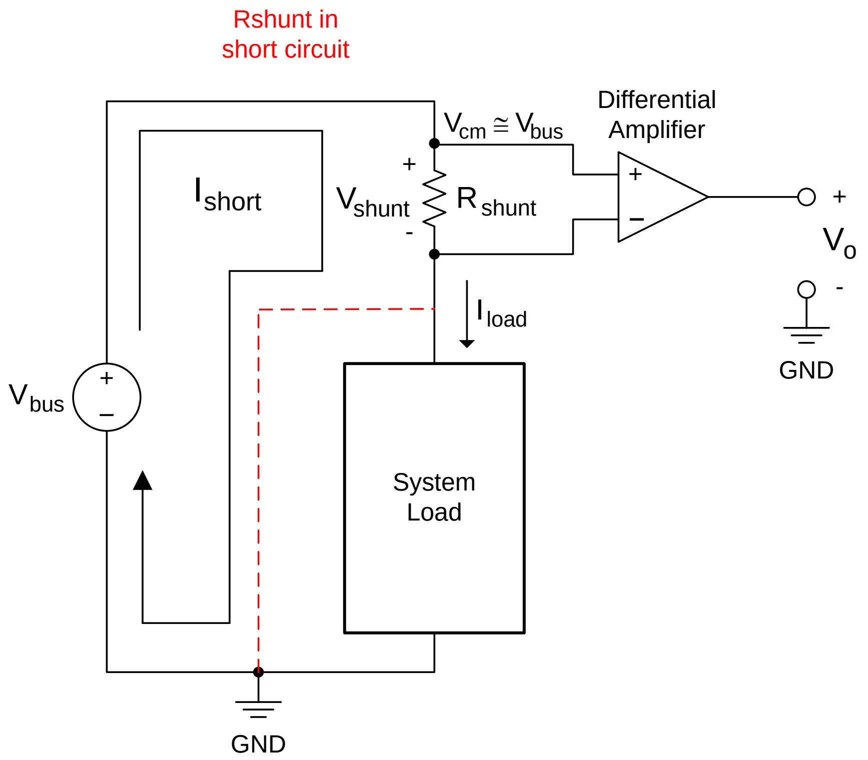
- For samples of the devices mentioned in this presentation, please follow the appropriate link
  - INA170, CSM, voltage output, 2.7V<Vcm<60V, Vos=1mV(max)
  - INA282, CSM, voltage output, -14V<Vcm<80V, Vos=70uV(max)
  - INA326, IA, RRI/O, Vos=100uV(max)
  - INA826, IA, RRO, Iq=200uA(typ), 2.7V<Vsupply<36V
  - INA149, DA, Vcm=+/-275V, unity gain
  - INA219, CSM, digital, 0V<Vcm<26V, Vos=50uV(max)
  - INA138/168, CSM, current output, 2.7V<Vcm<36V/60V, Vos=1mV(max)
  - INA193, CSM, voltage output, -16V<Vcm<80V, Vos=2mV(max)

Backup

Load Short



Rshunt not in short circuit
Ishort
System Load
Vbus
Iload
Differential Amplifier
Vshunt
Rshunt
Vcm ≅ GND
Vo
GND
GND



Rshunt in short circuit
Vcm ≅ Vbus
Differential Amplifier
Ishort
Vshunt
Rshunt
Vo
Iload
Vbus
System Load
GND
GND

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