

Current Sensing with Different Types of Amplifiers

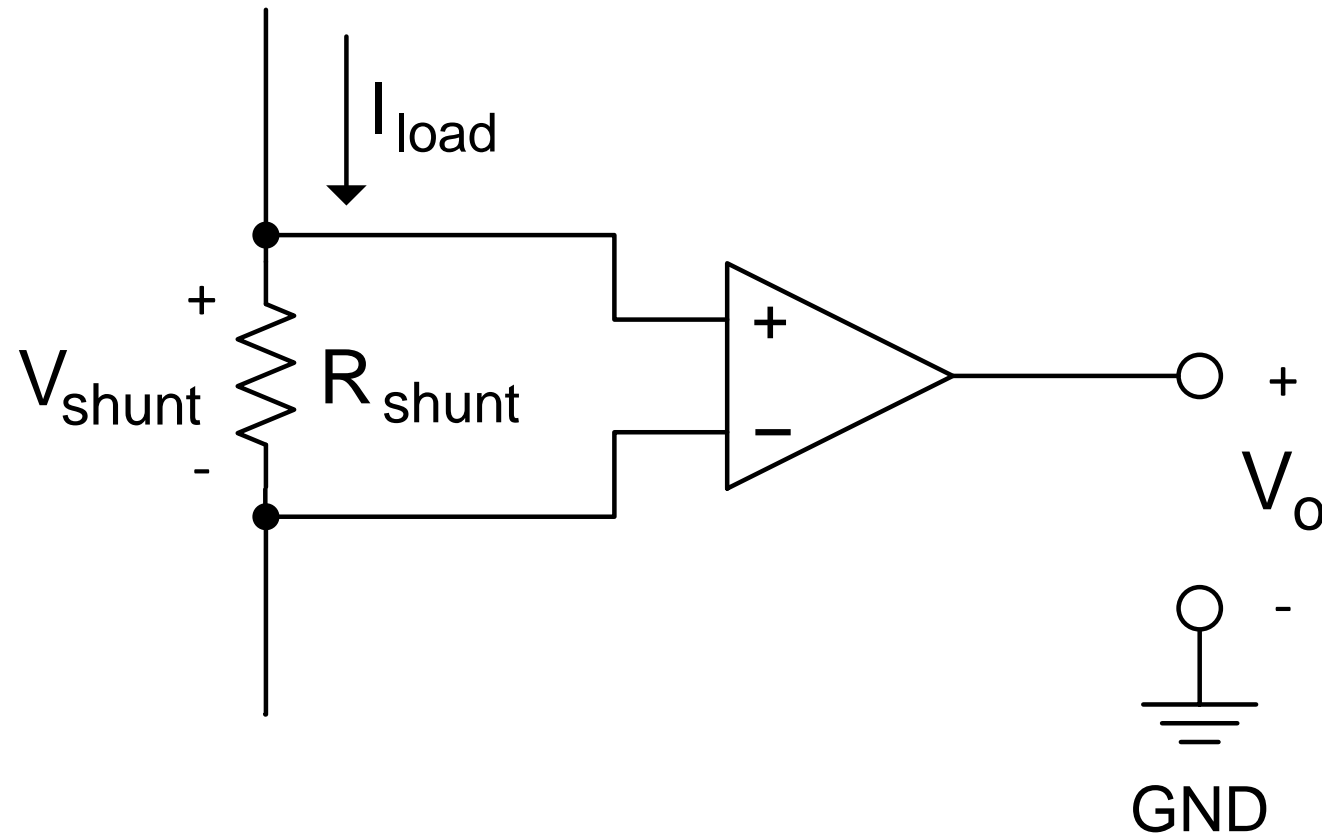
TI Precision Labs – Current Sense Amplifiers

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Hello, and welcome to the TI precision labs series on current sense amplifiers. My name is Chuk Udegbugue, and I'm a product marketing engineer in the Current & Position Sensing product line. In this video, we will introduce the different types of amplifiers used for current sensing, and the strengths and weaknesses of each.

Direct current sensing



- **Things to know:**

- Based on Ohm's law
- Shunt resistor in series with load
- Invasive measurement- R_{SHUNT} adds to system load
- Sensing circuit not isolated from system load

- **Recommend when:**

- Currents are $< 100A$
 - Higher currents possible with appropriate shunt resistor and design techniques
- System can tolerate power loss
- Low voltage
- Load current not very dynamic
- Isolation not required (though it can be accomplished)

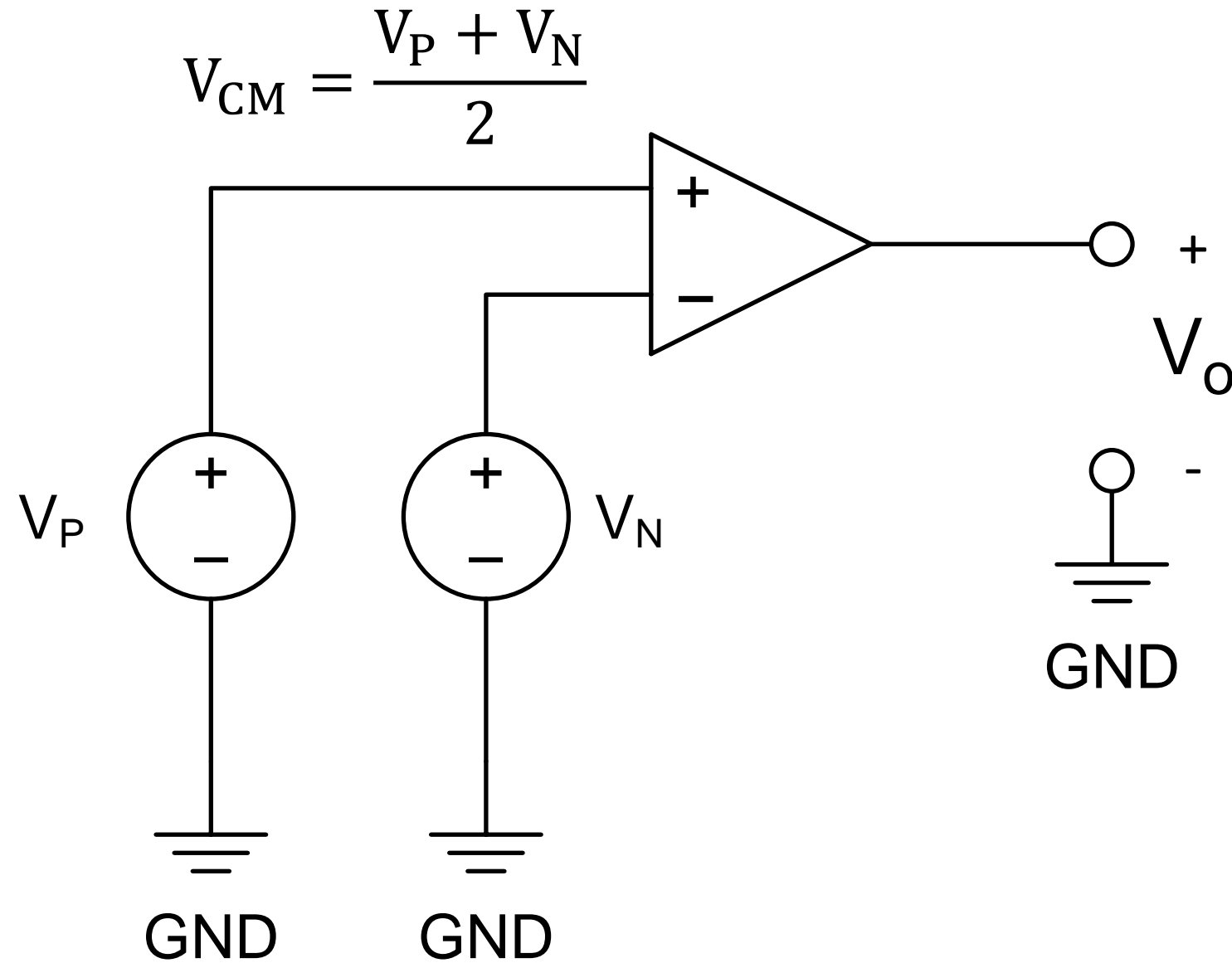
In today's training, I will introduce the basic concept of direct current sensing. This method is based on Ohm's law, where load current generates a voltage across the sense element, typically a shunt resistor. This shunt voltage, or sense voltage, is measured to determine the current level. It is an invasive measurement method where power is dissipated by the shunt resistor.

The sense voltage across the shunt resistor is small, typically in the millivolt range, so it must be amplified and signal-conditioned to be processed by systems downstream of the current sensing circuit.

I will review the pros and cons of various implementations so that you can choose the best method for your application.

Before we can look at the various circuit options, I need to introduce some basic concepts that will help you better understand the application.

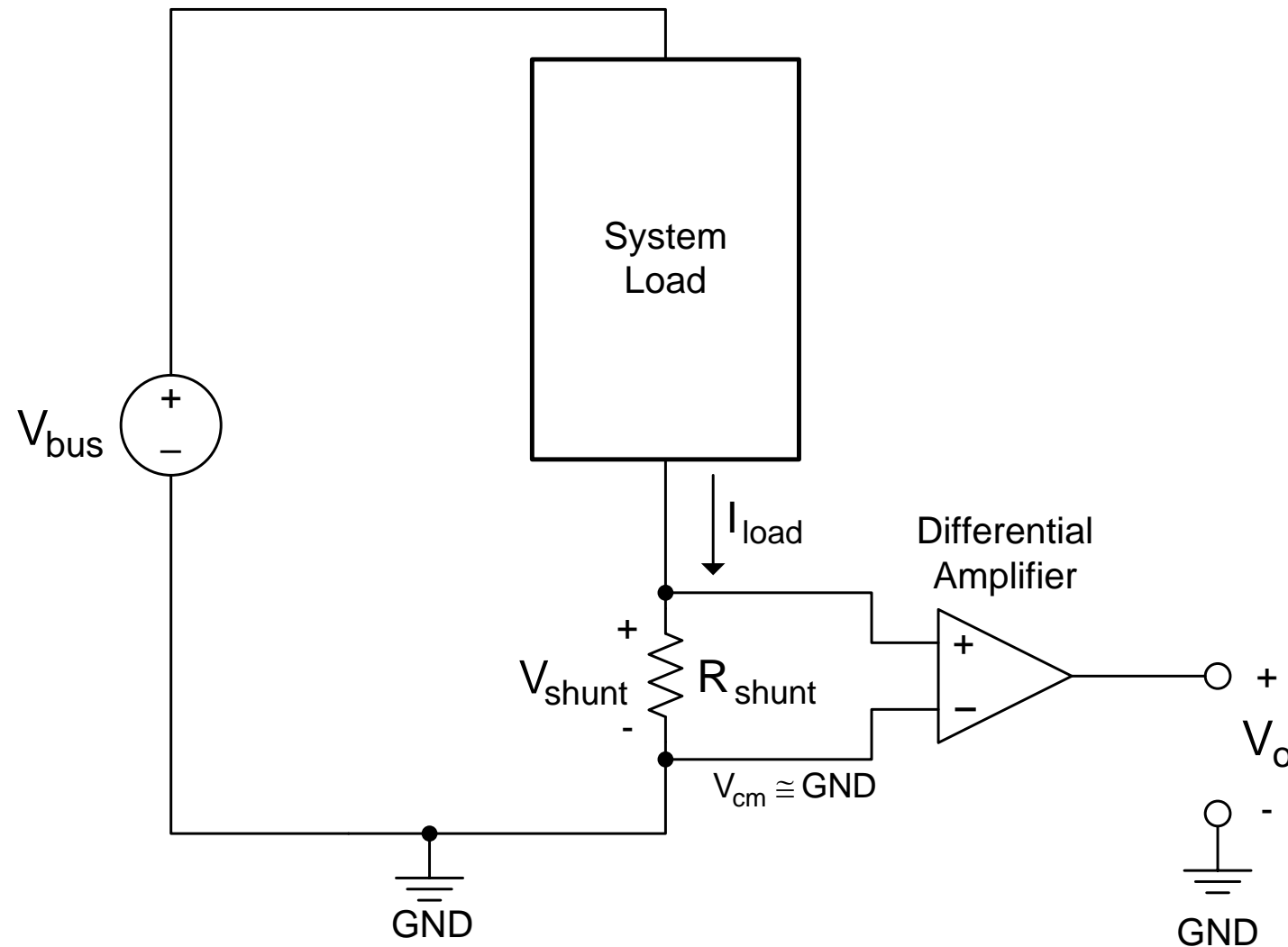
Input common-mode voltage (V_{CM})



The first concept is input common-mode voltage, V_{cm} . Common-mode voltage is defined as the average voltage of the two input pins of a differential amplifier, as shown in the figure. Depending on your measurement technique and application requirements, your amplifier may be required to either handle very low or very high common mode voltages.

Low-side sensing

Shunt resistor placed between load & ground



- **Pros**

- $V_{CM} \approx 0V$
- Simple
- Inexpensive

- **Cons**

- Can't detect load shorts to ground
- Single-ended measurement
- System $GND = I_{LOAD} * R_{SHUNT}$

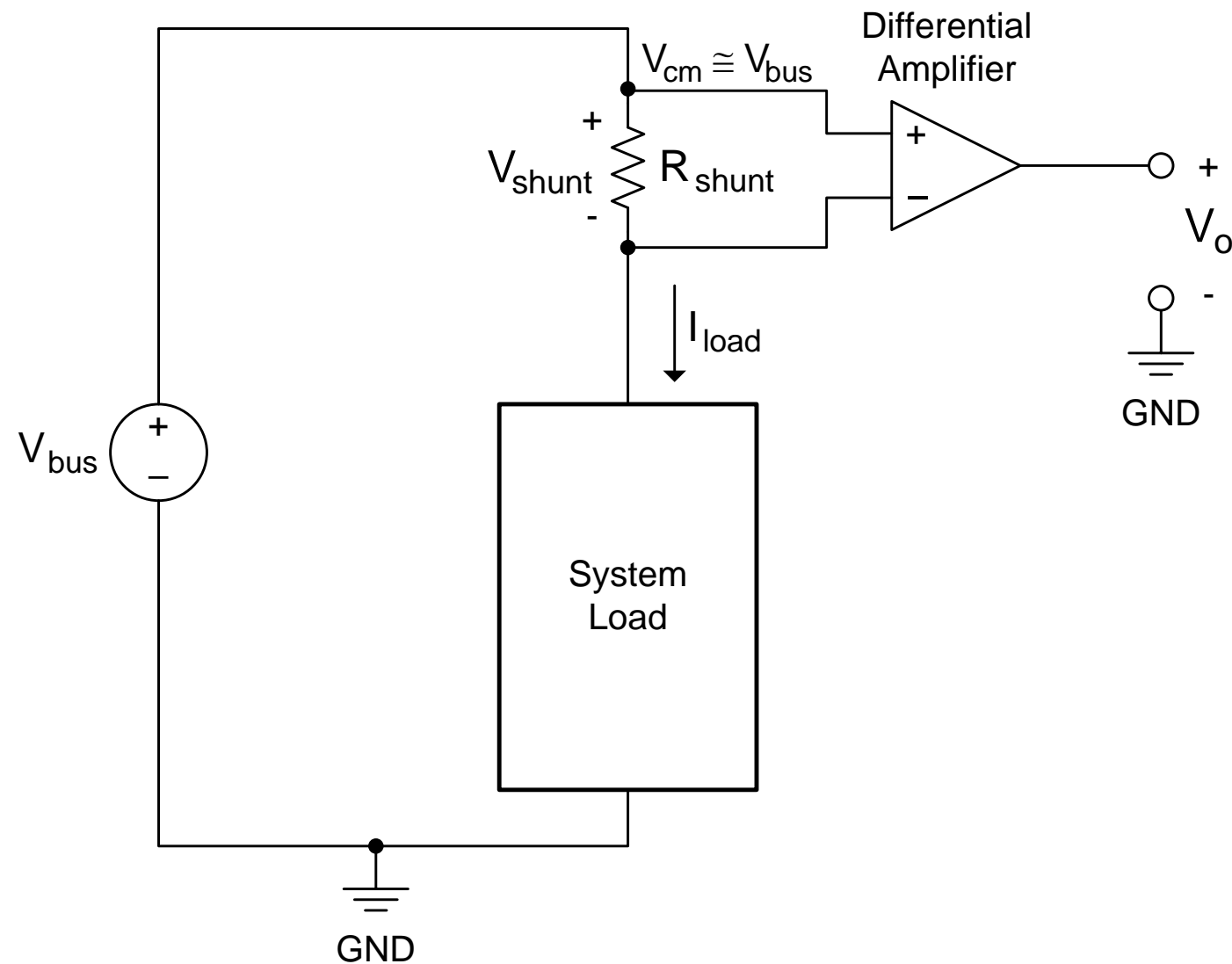
The next concept is low-side or high-side sensing.

A low-side implementation has the shunt resistor (R_{shunt}) placed between the system load and ground. This results in the common mode voltage being essentially 0V. This type of configuration is usually simple and inexpensive to design.

However, there are two disadvantages: First, it disturbs the ground seen by the load, and second, it prevents the ability to detect load shorts to ground.

High-side sensing

Shunt resistor placed between supply & load



- **Pros**

- Can detect load shorts to ground
- Monitors current directly from source

- **Cons**

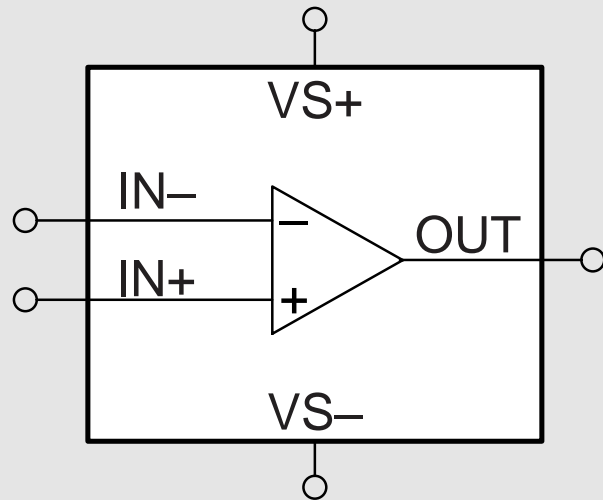
- $V_{CM} \approx V_{BUS}$
 - Requires amplifier with high V_{CM} range, depending on V_{BUS} voltage

A high-side implementation has the shunt resistor placed between the supply voltage and the load, resulting in the common mode voltage being essentially equal to the bus voltage.

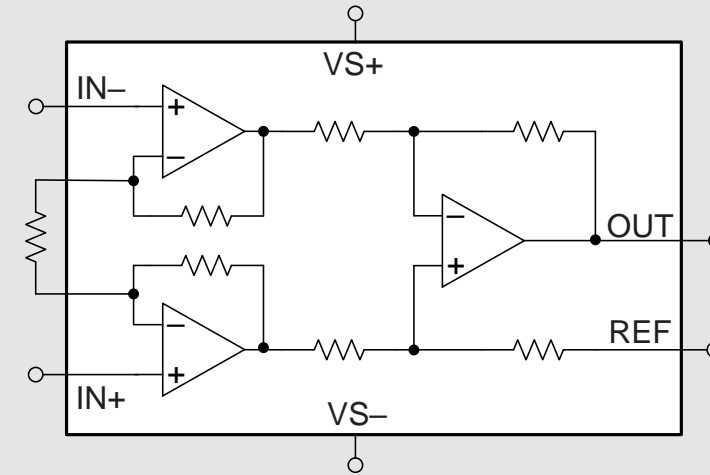
This allows for the system to not have any ground disturbance and to identify ground shorts, but depending on the system voltage, the system may require an amplifier with very high common mode voltage capability.

Types of differential amplifiers

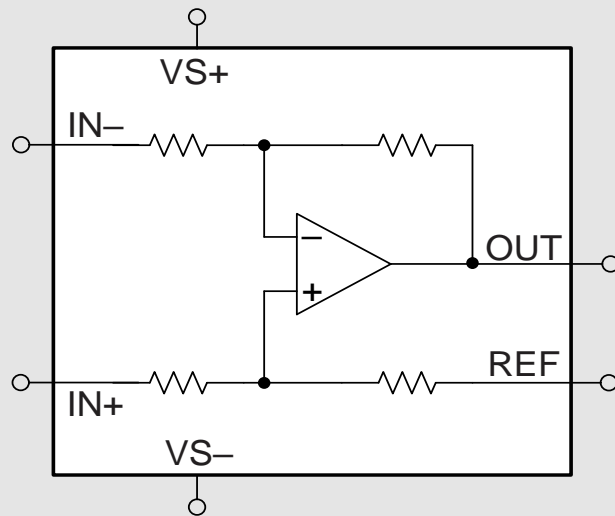
Operational amplifier



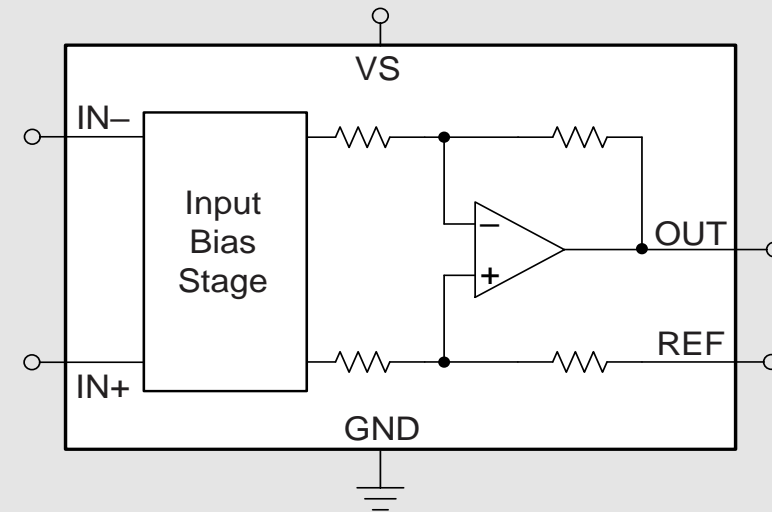
Instrumentation amplifier



Difference amplifier



Current sense amplifier

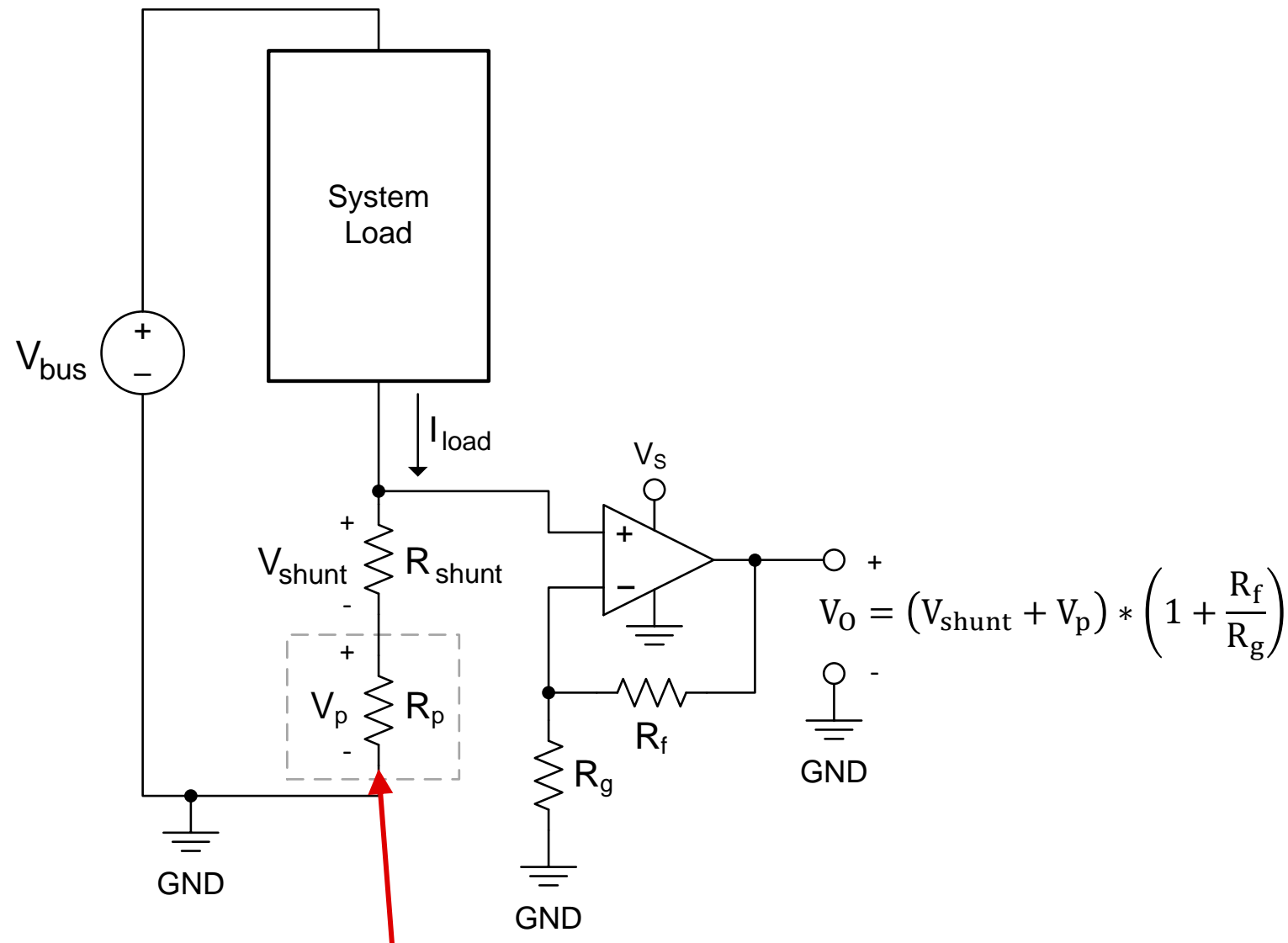


Direct current sensing typically uses a differential input amplifier to gain up the small sense voltage. There are four main types of differential amplifiers that are used for current measurement:

Operational amplifiers, or op-amps for short,
Instrumentation amplifiers,
Difference amplifiers,
and current sense amplifiers – also known as current shunt monitors.

Each of these has their own pros and cons which we will now discuss.

Operational amplifier (op amp)



Parasitic impedance to GND
introduces error

- **Pros**

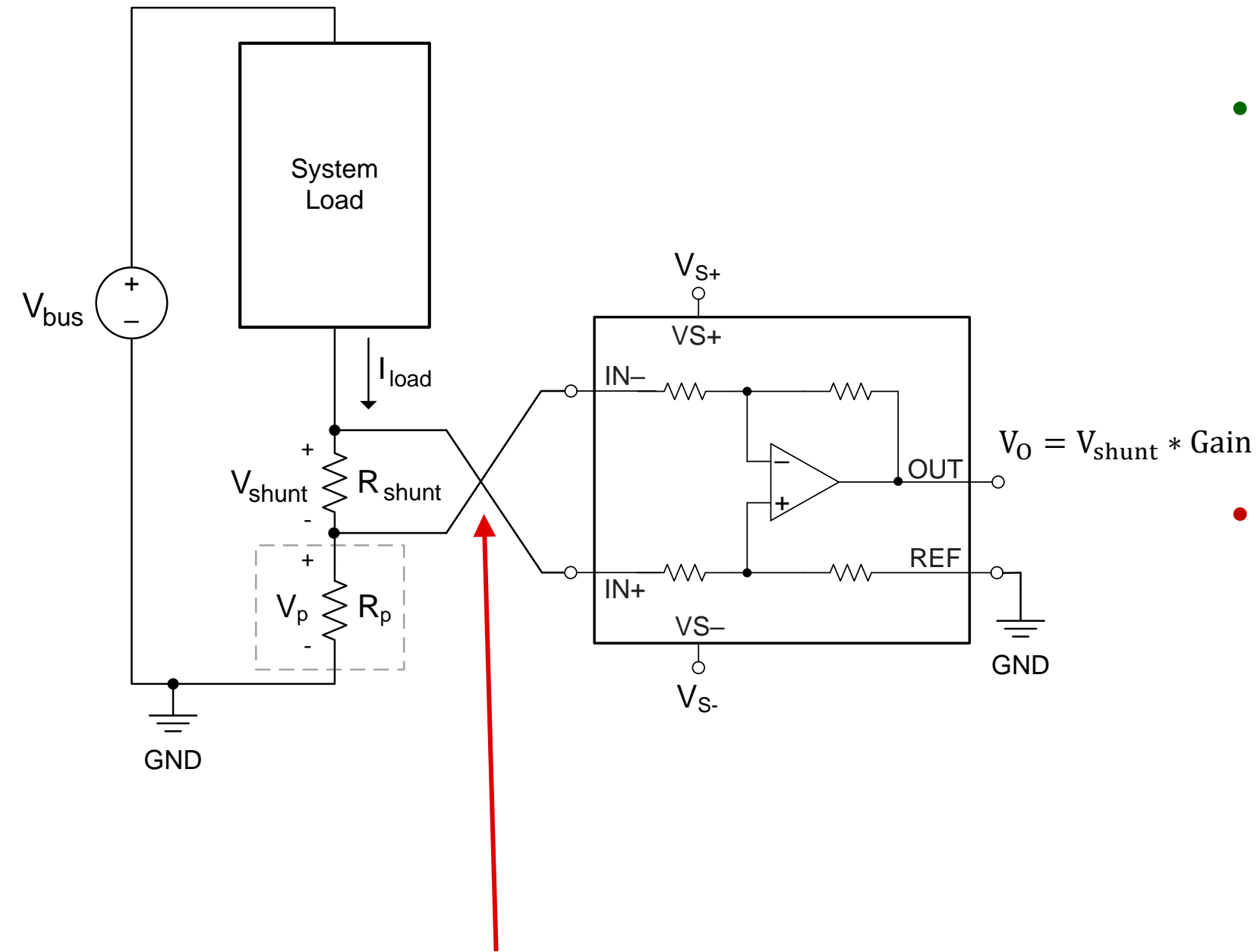
- Large open-loop gain
- Often very low cost

- **Cons**

- Accuracy is set by external components
- Low-side only: $V_{CM} \approx GND$
- With a single-ended input, PCB parasitics will create additional error

Op amps offer the most basic implementation and typically are used in lower accuracy, low cost applications. However, the cost savings are offset if high accuracy external components are used to increase precision. Because the common-mode voltage of an op amp is limited to its supply voltage, these are best suited for low-side measurement. If implemented with a single-ended input to the op amp, any parasitic impedances on the printed circuit board (PCB) between R_{shunt} and GND will create errors due to an additional voltage drop.

Difference amplifier (DA)



Solves PCB parasitic issue

- **Pros**

- Can be used for either high or low-side current sensing
- Can tolerate very large common-mode voltages
 - Large resistive divider on input pins

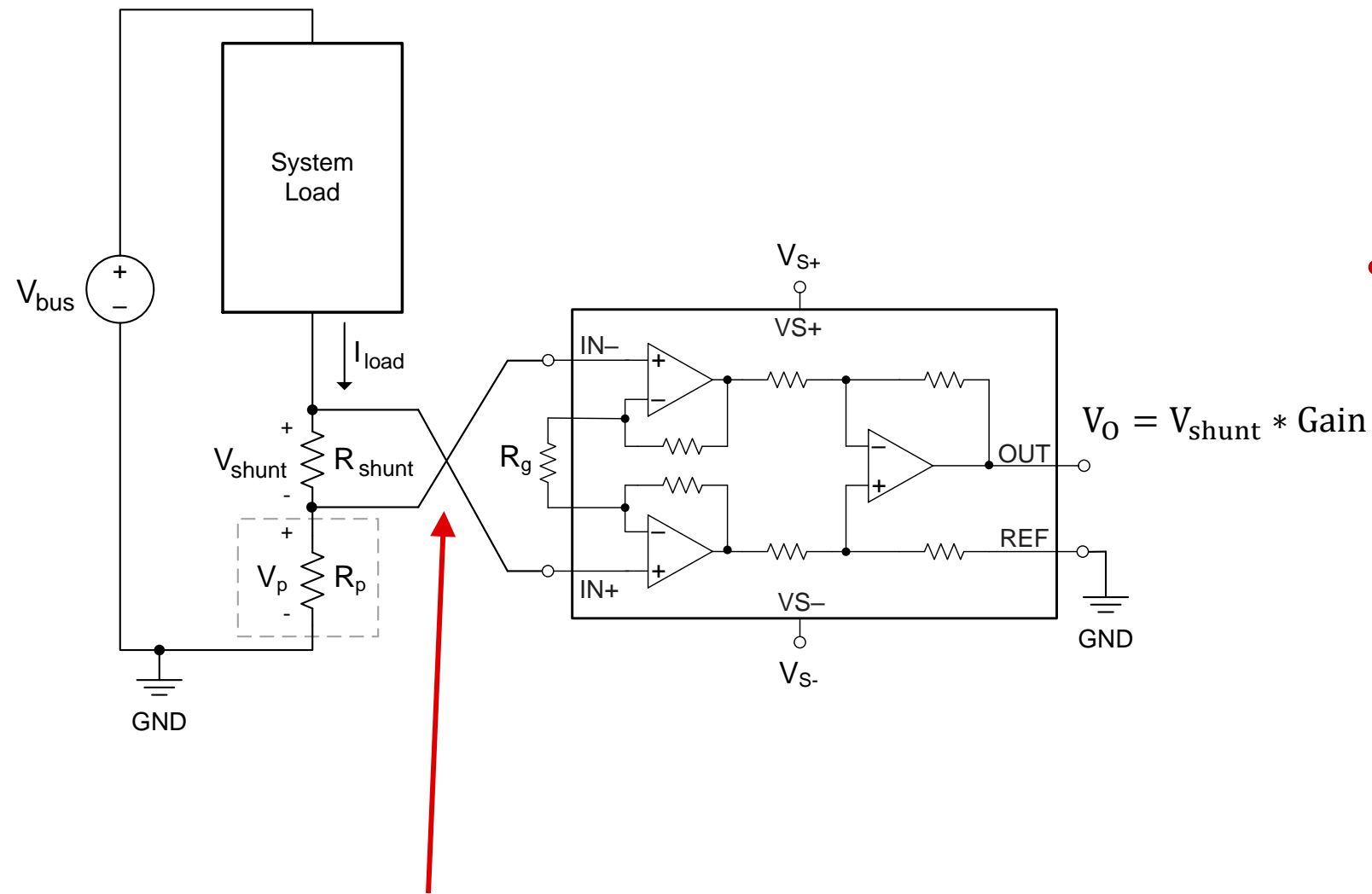
- **Cons**

- Resistor network loads the system
 - Must ensure system impedance is significantly smaller than DA input impedances

Difference amplifiers are designed to convert small differential signals to large single ended signals. The typical voltage drop across R_{SHUNT} is small so as not to add to the overall system load. Therefore the difference amplifier architecture is well-suited to most current sensing applications. Because the input voltage is differential, errors due to PCB parasitics are removed.

These devices have resistor divider network at the inputs which allows large common-mode voltages and enables high-side or low-side measurement. However, this resistor network can also load the system, introducing errors if not handled carefully.

Instrumentation amplifier (IA)



Solves PCB parasitic issue

- **Pros**

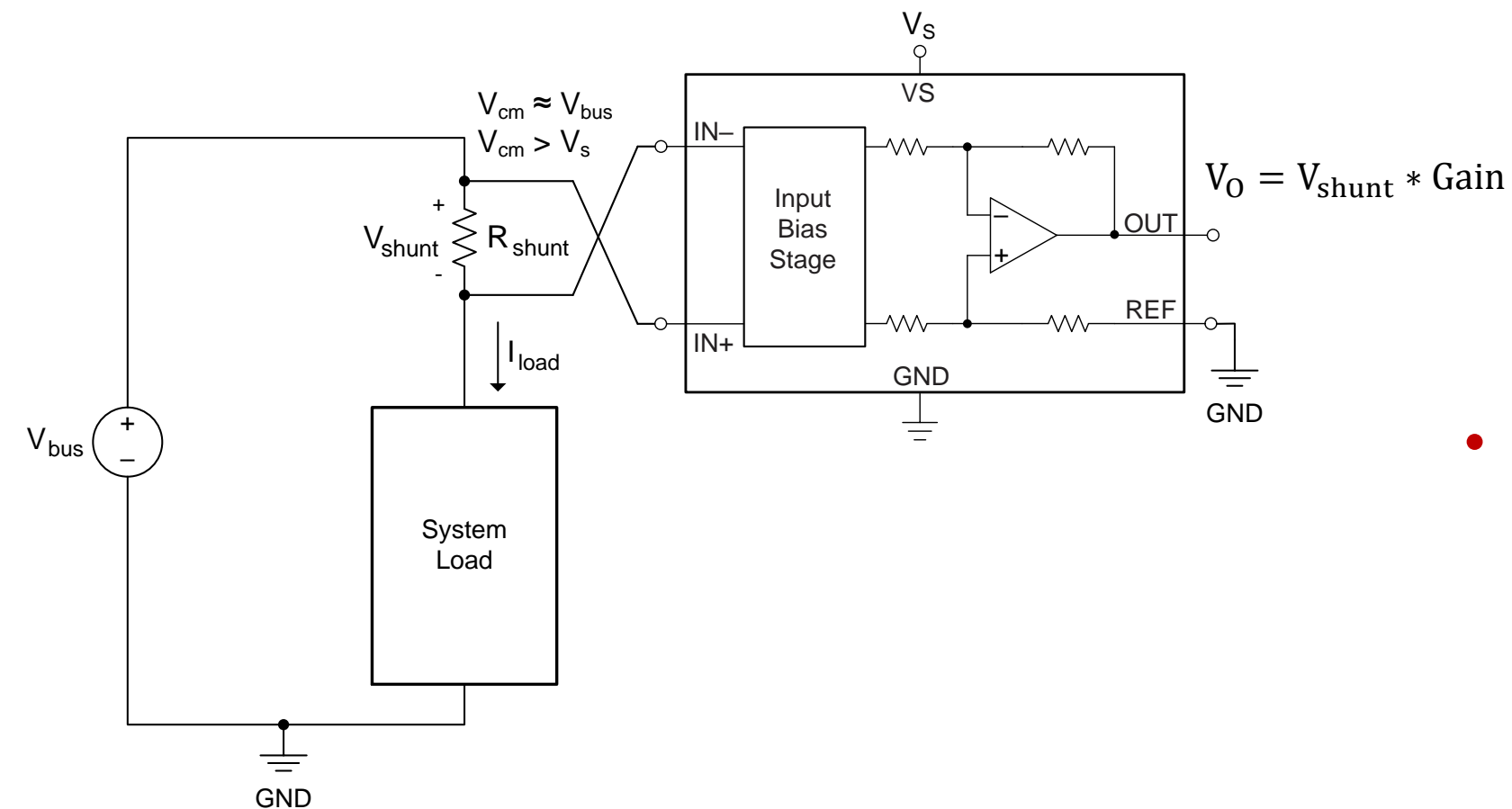
- Large input impedance allows for measuring very small currents
- Change gain with external resistor

- **Cons**

- Common-mode voltage must remain within supply voltage, $V_{CM} \leq V_S$
- Usually used for low-side sensing, but can be used for high-side depending on common-mode voltage

Instrumentation amplifiers are a combination of a difference amplifier with a buffer stage on each of the inputs. This very large input impedance enables the measuring of very small currents. However, the architecture limits the use to applications where the common mode voltage is within the supply voltage range. Like difference amplifiers, the differential input voltage removes errors due to PCB parasitics.

Current sense amplifier (CSA)



• Pros

- Unique floating input stage topology allows for $V_{CM} > V_s$ and large input impedance
- Precision integrated gain network maximizes accuracy and minimizes drift

• Cons

- Usually only offered at fixed gain
- Greater accuracy at higher currents

Current sense amplifiers (also called current shunt amplifiers or current shunt monitors) are specialized amplifiers with a unique input stage, that enables the common mode voltage to be much higher than the supply voltage. In addition, they integrate a high-precision, low-drift gain network that maximizes measurement accuracy. The input structure is such that limits the use cases where the ISHUNT is greater than tens of micro-amps.

When to choose a current sense amp

- Direct current sensing is a simpler to implement and lower cost method of current sensing than indirect magnetic methods
- Current sense amplifiers can be used in most applications and typically offer performance benefits over the alternatives

	Operational amplifier	Difference amplifier	Instrumentation amplifier	Current sense amp
Current range	mA's → 10's A	mA's → 10's A	nA's → 10's A	10s μ A's → 10's A
V_{CM} range	+V _s → -V _s	>>V _s → <<-V _s	+V _s → -V _s	>V _s → <-V _s
Strengths	Low cost* ease of use	High V _{CM} range	Can measure very small load currents	Accuracy, high V _{CM} range, high gain
Challenges	Accuracy*, V _{CM} range limited to V _s , minimum I _{LOAD} measurement limit, single-ended input	Minimum I _{LOAD} measurement limit, Low gain requires large V _{SHUNT}	V _{CM} range limited to V _s	Usually offered in fixed gains

* Depends on op amp selected

Direct current sensing is a simpler to implement and lower cost method of current sensing than indirect magnetic methods, and current sense amplifiers offer the most comprehensive set of features to maximize current measurement performance for the widest range of applications. The table shown on this slide summarizes the four types of amplifiers we have discussed in this video.

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](https://www.ti.com/currentsense).

Current Sensing with Different Types of Amplifiers

TI Precision Labs – Current Sense Amplifiers

Quiz

Current sensing w/ diff. types of amplifiers – quiz

1. Direct current sensing usually measures voltage across which circuit element?
 - a) Capacitor
 - b) Inductor
 - c) Resistor
 - d) Diode

2. In low-side sensing, the shunt resistor is placed between:
 - a) The system load and ground
 - b) The bus voltage and system load
 - c) The bus voltage and ground
 - d) Analog ground and digital ground

Current sensing w/ diff. types of amplifiers – quiz

3. A disadvantage of using op amps for current sensing is:
 - a) V_{CM} is limited to V_S of the op amp
 - b) Parasitic impedances on the PCB can cause errors
 - c) Accuracy may be dominated by external components
 - d) All of the above

4. The main advantage of using instrumentation amps for current sensing is:
 - a) Low cost
 - b) V_{CM} can be larger than the supply voltage V_S
 - c) The internal feedback network adds extra load to the system
 - d) Very low input bias current allows for measuring very small currents

Current sensing w/ diff. types of amplifiers – quiz

5. Which type of amplifier can handle V_{CM} larger than V_S ?
- a) Op amps
 - b) Difference amps
 - c) Instrumentation amps
 - d) Current sense amps
6. The maximum load current measurable with a current sense amp is:
- a) About 100A
 - b) About 10A
 - c) About 1A
 - d) About 100mA

Answers

Current sensing w/ diff. types of amplifiers – quiz

1. Direct current sensing usually measures voltage across which circuit element?
 - a) Capacitor
 - b) Inductor
 - c) Resistor**
 - d) Diode

2. In low-side sensing, the shunt resistor is placed between:
 - a) The system load and ground**
 - b) The bus voltage and system load
 - c) The bus voltage and ground
 - d) Analog ground and digital ground

Current sensing w/ diff. types of amplifiers – quiz

3. A disadvantage of using op amps for current sensing is:

- a) V_{CM} is limited to V_S of the op amp
- b) Parasitic impedances on the PCB can cause errors
- c) Accuracy may be dominated by external components
- d) All of the above

4. The main advantage of using instrumentation amps for current sensing is:

- a) Low cost
- b) V_{CM} can be larger than the supply voltage V_S
- c) The internal feedback network adds extra load to the system
- d) Very low input bias current allows for measuring very small currents

Current sensing w/ diff. types of amplifiers – quiz

5. Which type of amplifier can handle V_{CM} larger than V_S ?
- a) Op amps
 - b) Difference amps
 - c) Instrumentation amps
 - d) Current sense amps
6. The maximum load current measurable with a current sense amp is:
- a) About 100A
 - b) About 10A
 - c) About 1A
 - d) About 100mA