

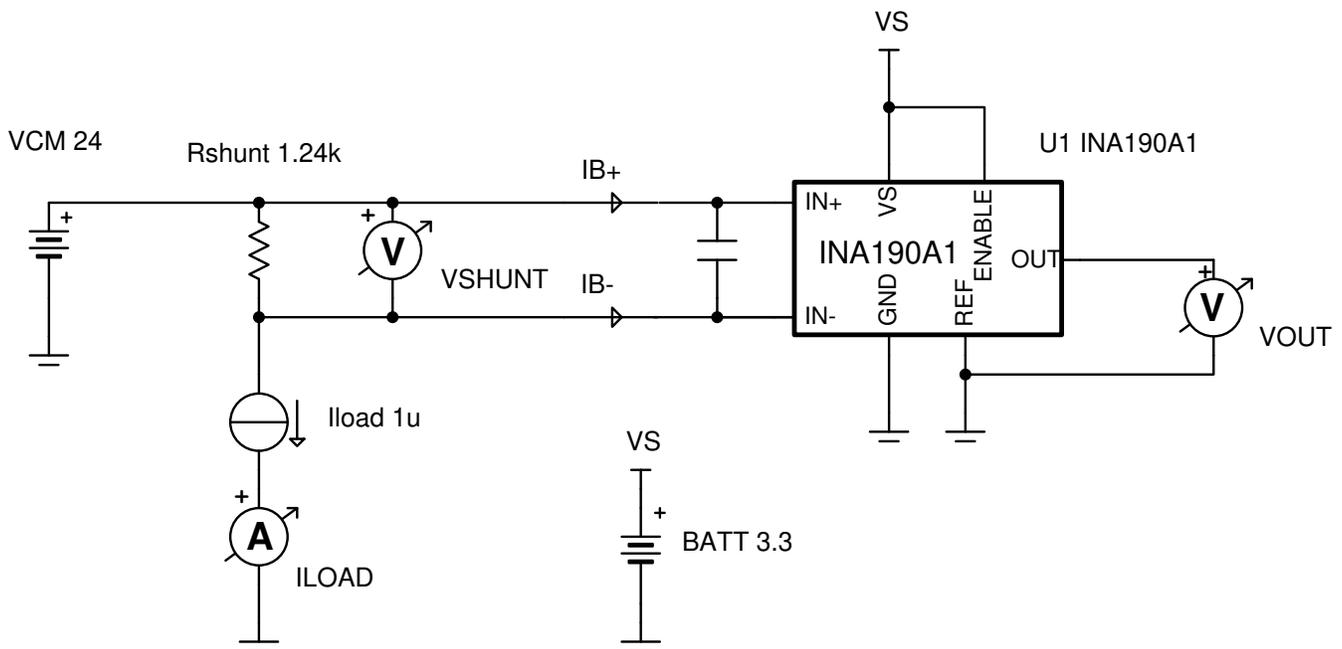
# Low (Microamp), High-Side, Current-Sensing Circuit with Current-Sensing Amplifier at High Voltage and Overtemperature



Input			Output		Supply			Temperature	
$I_{load\ Min}$	$I_{load\ Max}$	$V_{CM}$	$V_{OUT\ Min}$	$V_{OUT\ Max}$	$I_Q\ Max$	$V_{VS}$	$V_{ee}$	Low	High
1 $\mu$ A	104 $\mu$ A	$-0.1\ V \leq V_{CM} \leq 40\ V$	31.0 mV at 1 $\mu$ A	3.224 V at 104 $\mu$ A	65 $\mu$ A	3.3 V	GND (0 V)	0°C	85°C

## Design Description

This circuit demonstrates how to use a current sense amplifier to accurately and robustly measure small micro-amp currents and maximize dynamic range. The following error analysis can be applied to many current sense amplifiers. This design relies on using a precision, low input-bias current sense amplifier and analyzing the dynamic error due to input bias currents on large shunt resistors.



## Design Notes

1. The [Getting Started with Current Sense Amplifiers](#) video series introduces implementation, error sources, and advanced topic for using current sense amplifiers.
2. Choose a precision 0.1% shunt resistor to limit gain error at higher currents.
3. Choose a low input-bias current (high input-impedance) amplifier such as the [INA190](#).
4. Ensure VCM is within the operating VCM range of INA190: -0.1 V to 40 V.
5. Error significantly reduces if DC offsets are calibrated out with one-point calibration or if device operates under the same conditions as the [INA190 Low-Supply, High-Accuracy, Low- and High-Side Current-Shunt Monitor With Picoamp Bias Current and Enable](#) data sheet specifies ( $V_{VS} = 1.8\text{ V}$ ,  $V_{CM} = 12\text{ V}$ ,  $V_{REF} = 0.9\text{ V}$ ,  $T_A = 25^\circ\text{C}$ ). A two-point calibration can be done to eliminate gain error.
6. It is recommended to add  $\geq 1\text{ nF}$  input differential capacitor to INA190 inputs when working with large shunt resistors and DC currents.
7. Follow best practices for layout according to the data sheet: decoupling capacitor close to VS pin, routing the input traces for IN+ and IN- as a differential pair, and so forth.

## Design Steps

1. Given the design requirements, ensure the shunt resistor achieves a maximum total error of 3.51% at  $1\text{ }\mu\text{A}$  load current. Assume all offset and gain errors are negative. Note that error due to input bias current ( $I_{IB}$ ) is a function of the  $V_{SHUNT}$  and input differential impedance ( $R_{DIFF}$ ) where  $R_{DIFF} = I_{IB+}/V_{DIFF}$ . Since  $I_{IB-}$  starts around  $+500\text{ pA}$  and decreases as  $V_{SHUNT}$  increases, this generates a negative input offset error. See the [IB+ and IB- vs Differential Input Voltage](#) plot in the data sheet.

$$T_{MIN} = 0^\circ\text{C}; T_{MAX} = 85^\circ\text{C}$$

$$I_{LOAD\_MINIMUM} = 1\text{ }\mu\text{A}$$

$$R_{SHUNT} = 1240\Omega, 0.1\%$$

$$V_{VS} = 3.3\text{V}; V_{CM} = 24\text{V}; V_{REF} = \text{GND} = 0\text{V}$$

$$V_{OSI\_MAX} = -15\text{ }\mu\text{V}$$

$$V_{OS\_CMRR\_MAX} = |12\text{V} - V_{CM}| \cdot 10^{-\frac{CMRR_{MIN}}{20\text{dB}}} = 12\text{V} \cdot 10^{-\frac{132\text{dB}}{20\text{dB}}} = -3.01\text{ }\mu\text{V}$$

$$V_{OS\_PSRR\_MAX} = |1.8\text{V} - V_{VS}| \cdot PSRR_{MAX} = 3.2\text{V} \cdot 5\frac{\mu\text{V}}{\text{V}} = -7.5\text{ }\mu\text{V}$$

$$V_{OS\_RVRR\_MAX} = |0.9\text{V} - V_{REF}| \cdot RVRR_{MAX} = 0.9\text{V} \cdot 10\frac{\mu\text{V}}{\text{V}} = -9\text{ }\mu\text{V}$$

$$V_{OS\_Drift\_MAX} = |25^\circ\text{C} - T_{MAX}| \cdot \left(\frac{dV_{OS}}{dT}\right)_{MAX} = 60^\circ\text{C} \cdot 80\frac{\text{nV}}{^\circ\text{C}} = -4.8\text{ }\mu\text{V}$$

$$V_{OS\_IB\_MAX} = \text{func}\{V_{SHUNT}\} = R_{SHUNT} \cdot \left[ \frac{-V_{SHUNT}}{R_{DIFF}} + I_{IB\_Typ} \right] = 1240\Omega \cdot \left[ \frac{-1.24\text{mV}}{2.3\text{M}\Omega} + 0.5\text{nA} \right] = -48.5\text{nV}$$

$$V_{OS\_MAX} = V_{OSI\_MAX} + V_{OS\_CMRR} + V_{OS\_PSRR} + V_{OS\_RVRR} + V_{OS\_Drift\_Max} + V_{OS\_IB\_MAX}$$

$$V_{OS\_MAX} = -39.4\text{ }\mu\text{V}$$

$$R_{shunt\_tolerance} = -0.1\% = 0.001$$

$$GE_{25C\_MAX} = -0.3\% = -0.003$$

$$GE_{Drift\_MAX} = -7\frac{\text{ppm}}{^\circ\text{C}} \cdot (85^\circ\text{C} - 25^\circ\text{C}) \cdot 10^{-6} = -0.00042$$

$$\text{Gain}_{MAX} = 25 \cdot (1 + GE_{25C\_MAX} + GE_{Drift\_MAX}) = 25 \cdot (0.99758) = 24.940\text{ V/V}$$

$$V_{OUT\_MIN\_1\mu\text{A}} = [V_{OS\_MAX} + I_{LOAD} \cdot R_{SHUNT} \cdot (1 + R_{shunt\_tolerance})] \cdot \text{Gain}_{MAX} = 29.9\text{ mV}$$

$$V_{OUT\_IDEAL\_1\mu\text{A}} = [I_{LOAD\_MINIMUM} \cdot R_{SHUNT}] \cdot \text{Gain} = 31.0\text{ mV}$$

$$\text{Error} = 100 \cdot (V_{OUT\_MIN} - V_{OUT\_IDEAL}) / V_{OUT\_IDEAL}$$

$$\text{Error}_{1\mu\text{A}} = -3.51\%$$

$$\text{Error}_{6\mu\text{A}} = -0.91\%$$

2. Ensure the sensed current range fits within the output dynamic range of the device. This depends upon two specifications: Swing-to- $V_{VS}$  ( $V_{SP}$ ) and Zero-current Output Voltage ( $V_{ZL}$ ).  $V_{ZL}$  is specified over  $-40^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$  at  $V_{VS} = 1.8\text{ V}$ ,  $V_{REF} = 0\text{ V}$ ,  $V_{SENSE} = 0\text{ mV}$ ,  $V_{CM} = 12\text{ V}$ , and  $R_L = 10\text{ k}\Omega$ . Since data sheet conditions do not match the conditions of this design, extrapolate what the maximum  $V_{ZL}$  would be.
  - a. Calculate the maximum possible positive offset for testing conditions of  $V_{ZL}$ . Call this  $V_{OS\_TestConditions}$ .
  - b. Convert this input offset into an output offset by multiplying by maximum possible gain.
  - c. Determine the Headroom voltage by taking difference between the  $V_{ZL\_MAX}$  from data sheet and the previously determined maximum output offset.
  - d. Calculate  $V_{ZL\_MAX}$  in this design by adding the Headroom voltage to the maximum possible output offset for this design.
  - e. Ensure that the minimum  $V_{OUT}$  at  $1\mu\text{A}$  is greater than  $V_{ZL\_MAX}$ . Note  $V_{OUT\_MIN}$  at  $1\mu\text{A}$  assumes worst-case scenario of  $-1\%$  tolerance for  $R_{SHUNT}$  and negative input offsets.

$$V_{OS\_TestConditions} = V_{OSI\_MAX} + |0.9\text{V} - 0\text{V}| \cdot R_{VRR\_MAX} + |125^{\circ}\text{C} + 40^{\circ}\text{C}| \cdot \left(\frac{dV_{OS}}{dT}\right)_{MAX}$$

$$V_{OS\_TestConditions} = +15\mu\text{V} + 9\mu\text{V} + 13.2\mu\text{V} = 37.2\mu\text{V}$$

$$\text{Headroom} = V_{ZL\_MAX\_DATASHEET} - V_{OS\_TestConditions} \cdot \text{Gain}_{MAX}$$

$$\text{Headroom} = 3\text{mV} - 0.933\text{mV} = 2.07\text{mV}$$

$$V_{ZL\_MAX} = \text{Headroom} + V_{OS\_MAX} \cdot \text{Gain}_{MAX} = 2.07\text{mV} + (39.4\mu\text{V} \cdot 25.061\text{V/V}) = 3.06\text{mV}$$

$$V_{OUT\_MIN\_1\mu\text{A}} = 29.9\text{mV} > V_{ZL\_MAX}$$

- f. Now ensure the maximum  $V_{OUT}$  at  $104\mu\text{A}$  is less than  $V_{SP\_MIN}$ . Note  $V_{OUT\_MAX}$  at  $104\mu\text{A}$  assumes worst-case scenario of  $+1\%$  tolerance for  $R_{SHUNT}$  and positive input offsets.

$$V_{SP\_MIN} = V_{VS} - 40\text{mV} = 3.26\text{V}$$

$$V_{OUT\_MAX} = \left[ R_{SHUNT} \cdot (1 + R_{shunt\_tolerance}) \cdot I_{LOAD\_MAX} + V_{OS\_MAX} \right] \cdot \text{Gain}_{MAX}$$

$$V_{OUT\_MAX} = [1240\Omega \cdot (1.001) \cdot 104\mu\text{A} - 29.6\mu\text{V}] \cdot 25.061\text{V/V} = 3.234\text{V}$$

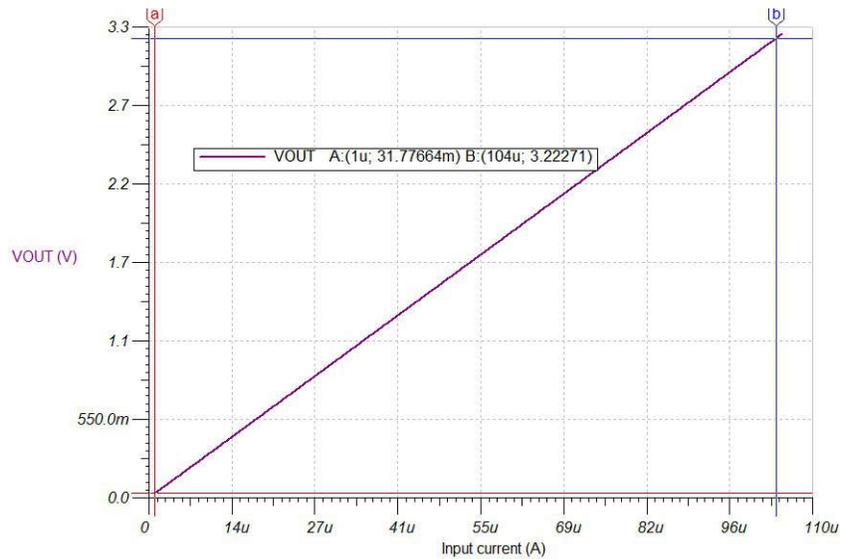
$$V_{OUT\_MAX} < V_{SP\_MIN}$$

3. Generate *Total Error vs Load Current* curves based upon the total error equations in Step 1. Do this for the typical and maximum data sheet specifications.

## Design Simulations

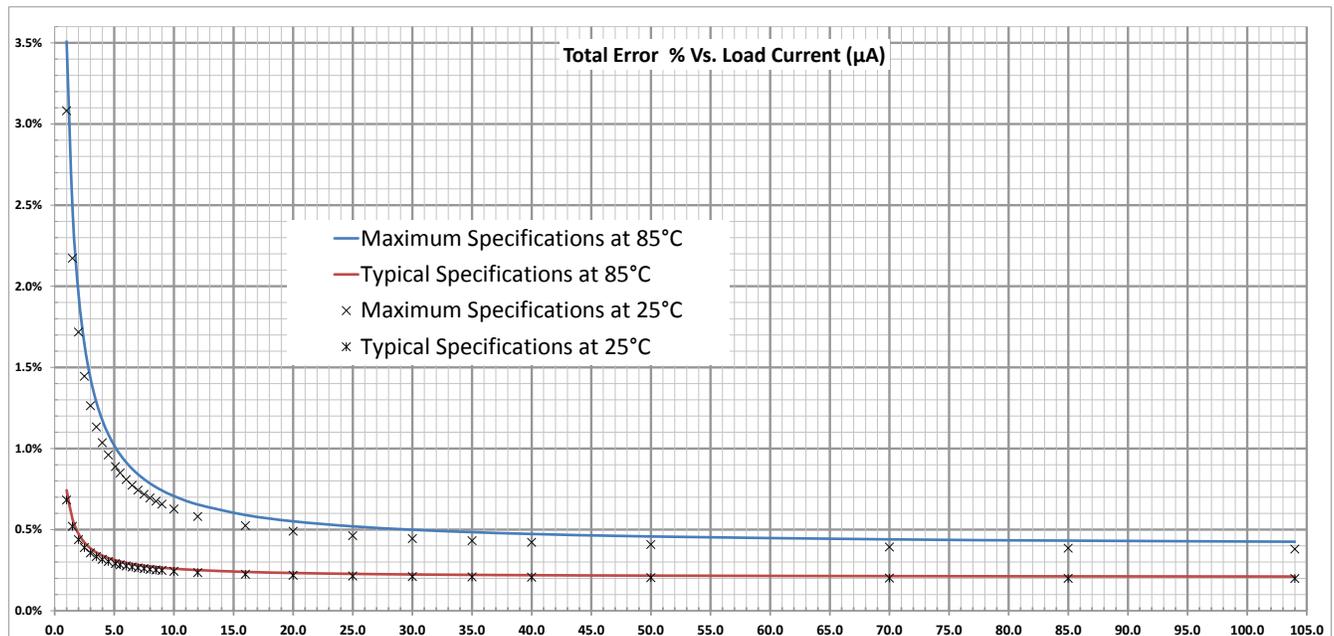
### DC Simulation Results

The following graph shows a linear output response for load currents from 1  $\mu\text{A}$  to 104  $\mu\text{A}$



### Total Error Calculations

The following graph shows the total absolute error over temperature using both the assured limit specifications and the typical specifications. Note that accuracy is limited by the offset voltage at the lowest current sensed and limited by gain error at higher currents. Active offset chopping limits the error due to temperature.



## Design References

See [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

See circuit SPICE simulation file [SBOMA16](#).

## Getting Started with Current Sense Amplifiers video series

[Getting started with current sense amplifiers](#)

## Application Note on Power-Saving Topologies for TI Current Shunt Monitors

[Extending Voltage Range of Current Shunt Monitor](#)

## Current Sense Amplifiers on TI.com

[Current sense amplifiers – Products](#)

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## Design Featured Current Shunt Monitor

INA190A1	
<b>V<sub>VS</sub></b>	1.8 V to 5 V (operating)
<b>V<sub>CM</sub></b>	-0.3 V to 42 V (survivability)
<b>V<sub>OUT</sub></b>	Up to (V <sub>VS</sub> ) + 0.3 V
<b>V<sub>OS</sub></b>	±3 μV to ±15 μV
<b>I<sub>Q</sub></b>	48 μA to 65 μA
<b>I<sub>IB</sub></b>	0.5 nA to 3 nA
<b>BW</b>	45 kHz at 25 V/V (A1 gain variant)
<b># of Channels</b>	1
<a href="#">INA190</a>	

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