Input Filter (Resistance) Error

TI Precision Labs – Current Sense Amplifiers

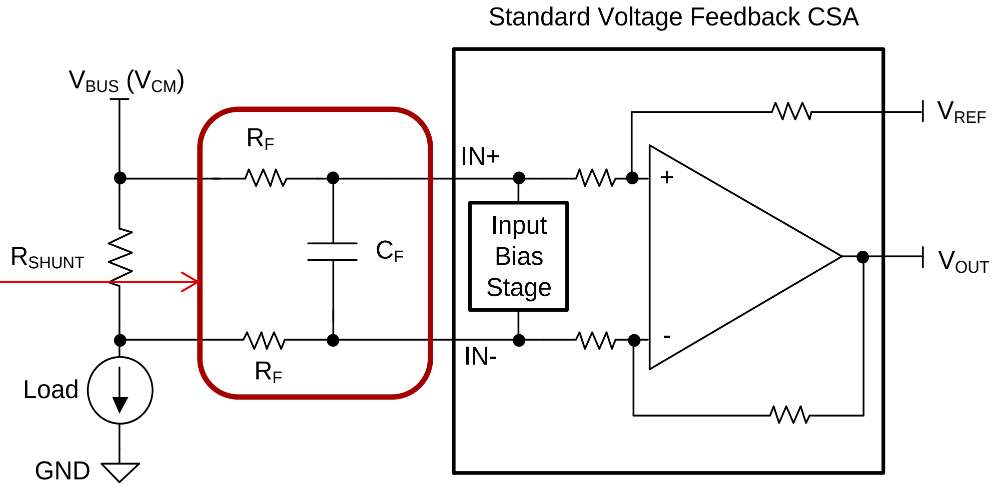
Presented and prepared by Peter Iliya

Input Filter Error for Current Sense Amplifiers (CSA)

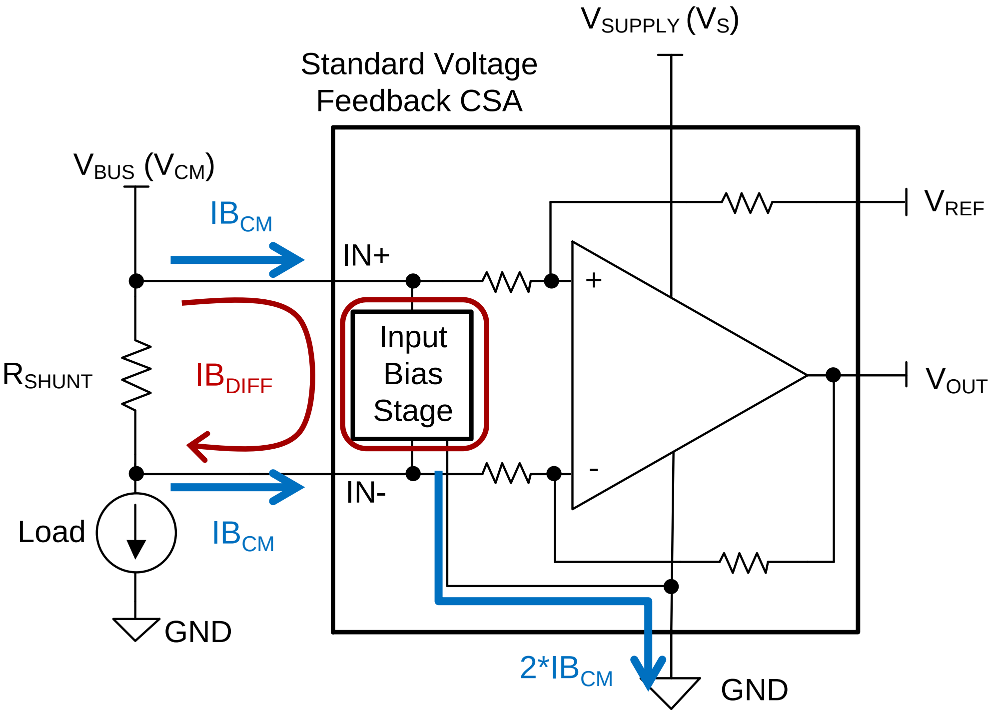
Device Errors:

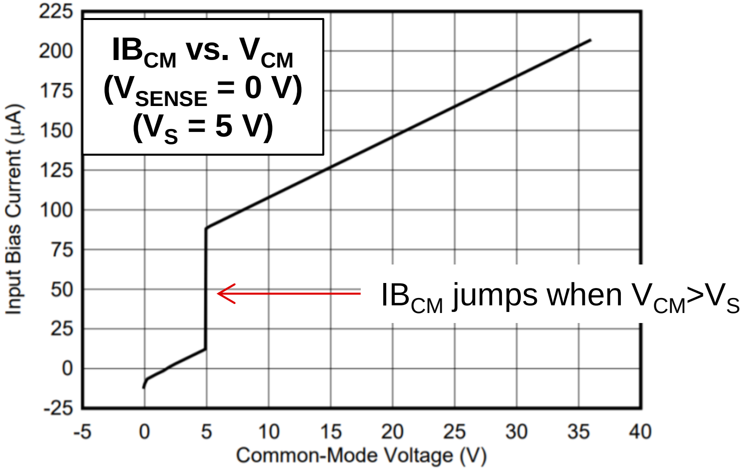
$$\varsigma_{RSS}(\%) \approx \sqrt{{e_{Vos}}^2 + {e_{CMRR}}^2 + {e_{PSRR}}^2 + {e_{Gain\_error}}^2 + {e_{Linearity}}^2 + {e_{Shunt\_tolerance}}^2 + {e_{Bias\_current}}^2 + {e_{Other}}^2}$$

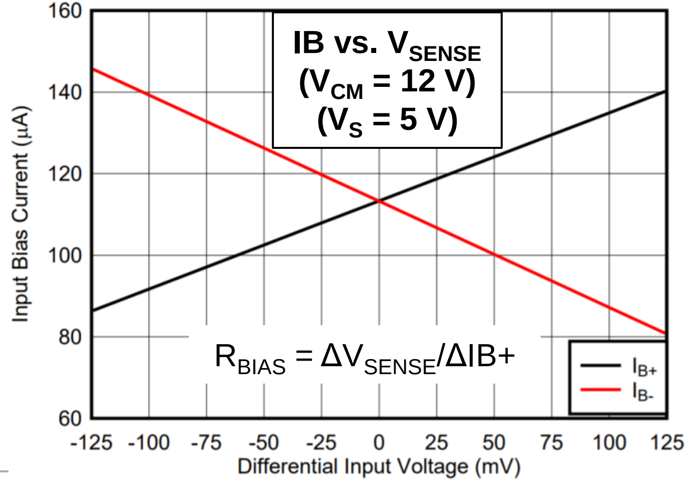
Input filter will decrease gain and add error.



The CSA Input Bias Stage

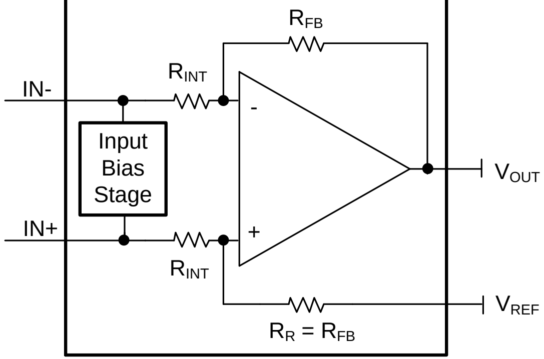






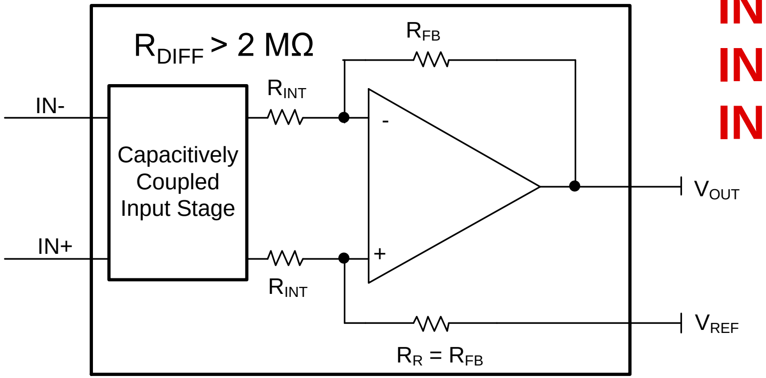
Four basic CSA topologies and example devices

Standard Single-Stage, Voltage-Feedback CSA



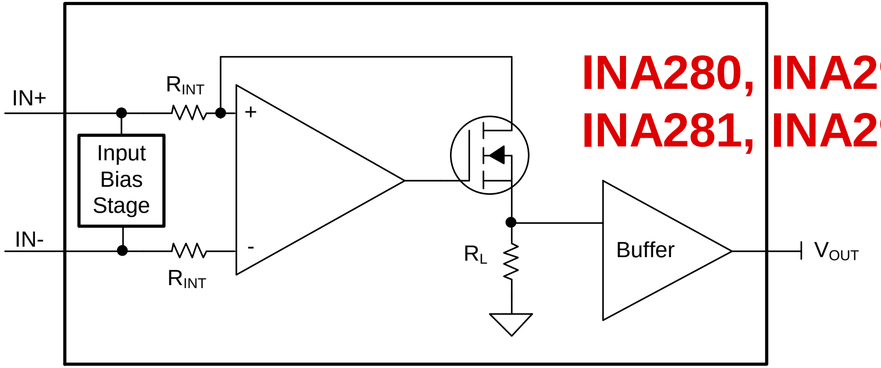
INA181
INA185
INA199
INA210

Capacitively-Coupled, High Input-Impedance CSA



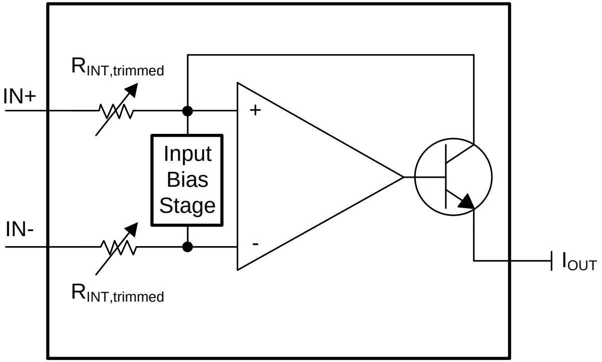
INA186
INA190
INA191

Current-Feedback CSA with Input Bias Stage



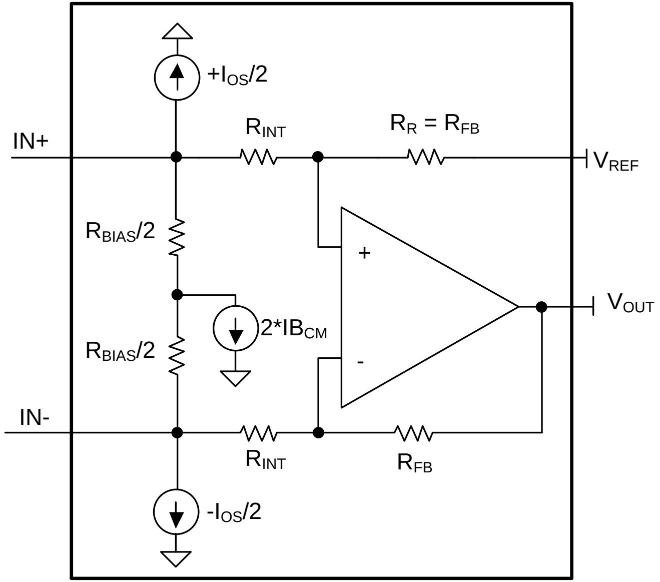
INA280, INA290
INA281, INA293

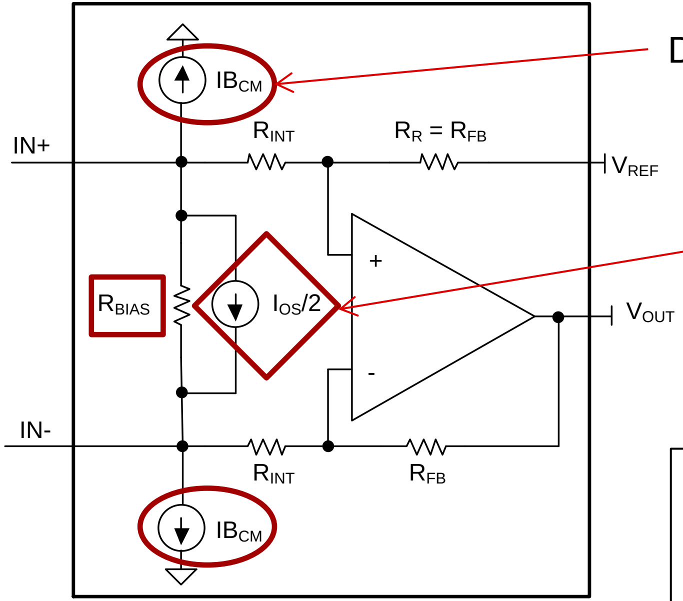
Current-Feedback, Current-Output CSA with Trimmed Transconductance Resistors



INA139
INA138
INA169
INA168

Modeling the CSA





Dependent upon V_{CM}

$I_{OS} = I_{IO} = (IB+) – (IB-)$

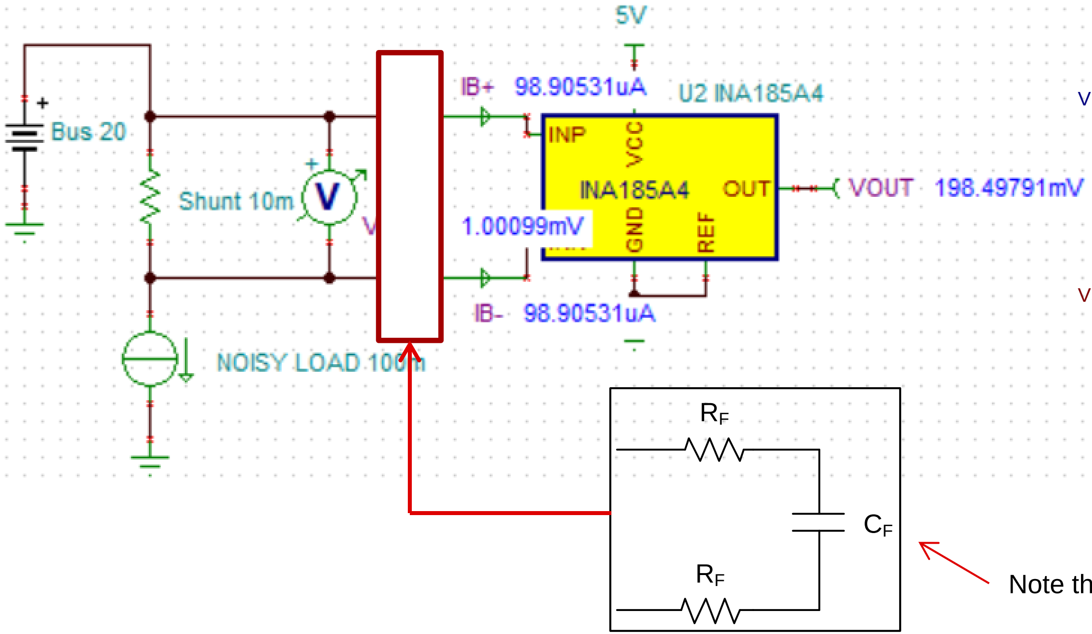
R_{FB}, R_{INT}, and R_{BIAS} all can vary ±20%

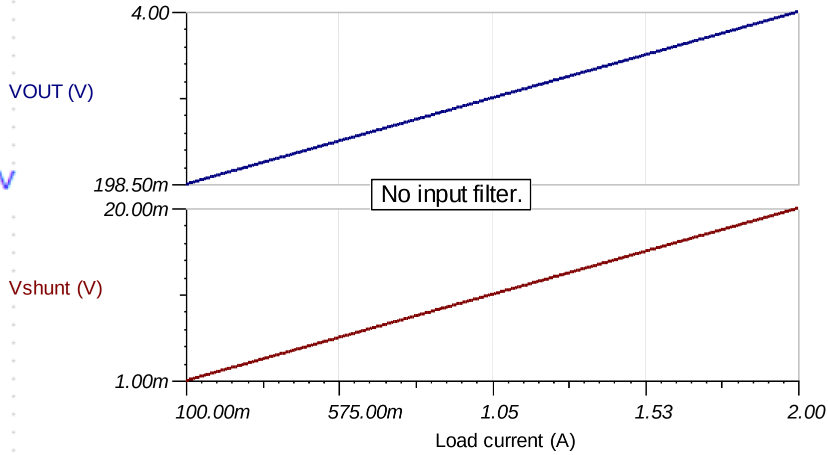
R_{FB}/R_{INT} = Device gain

R_{FB}/R_{INT} variation = Device Gain Error

Both models are equivalent

Example - Overview

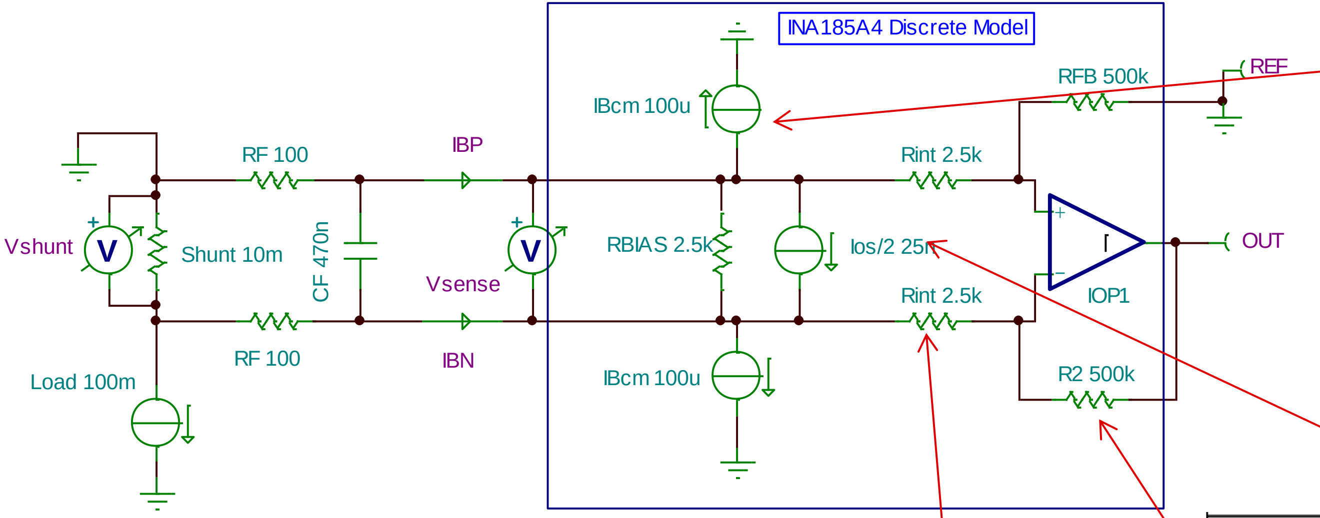




Note there is no maximum limitation to the value of C_F for the CSA.

Problem: Noisy load.
Solution: Insert **differential input filter** with 1.6 kHz cuttoff frequency.
Analysis: Use discrete simulation model of INA185 to determine new circuit gain and errors with 100-Ω/1% input resistors.

Example 1 – Analysis, create discrete model



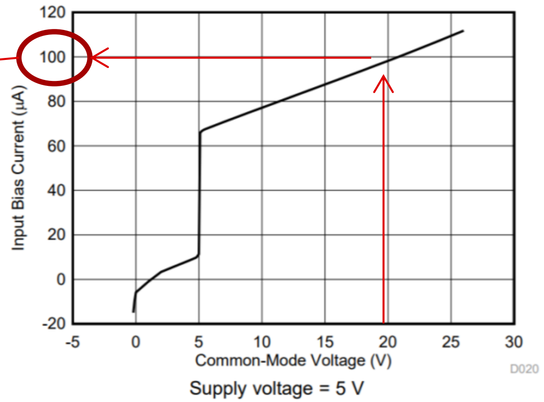


Figure 20. Input Bias Current vs Common-Mode Voltage

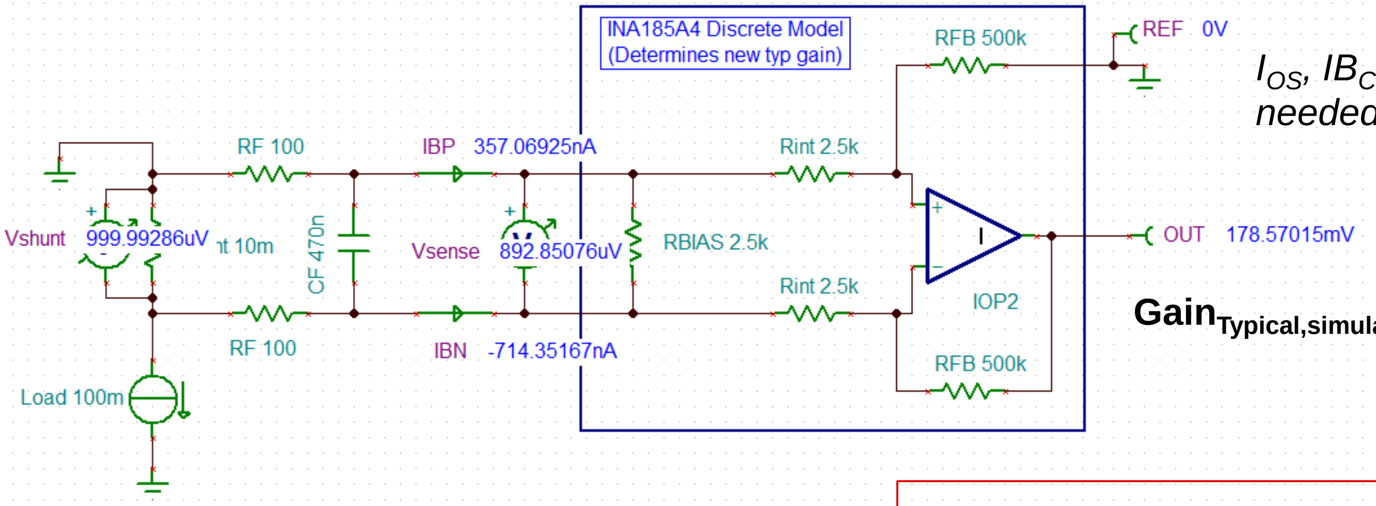
I_{IO}	Input offset current	±0.05	µA

Table 1. Input Resistance

PRODUCT	GAIN	R_{INT} (kΩ)
INA185A1	20	25
INA185A2	50	10
INA185A3	100	5
INA185A4	200	2.5

$$R_{FB} = Gain * R_{INT}$$

Example – Determine new gain (2 ways)



I_{OS}, IB_{CM}, and V_{BUS} sources are not needed to determine new gain.

$$\textbf{Gain}_{\textbf{Typical,simulated}} = \textbf{V}_{\textbf{OUT}}/\textbf{V}_{\textbf{SHUNT}} = \textbf{178.57 V/V}$$

$$\text{Gain Error Factor} = \frac{1250 \times R_{INT}}{(1250 \times R_F) + (1250 \times R_{INT}) + (R_F \times R_{INT})}$$

where:

- R_{INT} is the internal input resistor.
- R_F is the external series resistance.

$$Gain_{Typical} = Gain_{Device} * (Gain\ Error\ Factor)$$

$$Gain_{Typical} = 200\ V/V * \left(\frac{2.5\ \text{k}\Omega}{3 * 100\ \Omega + 2.5\ k\Omega}\right)$$

$$\boldsymbol{Gain_{Typical} = 178.57\ V/V}$$

Example – Determine positive gain error

What is maximum possible gain?

1. Increase internal resistors by +20%

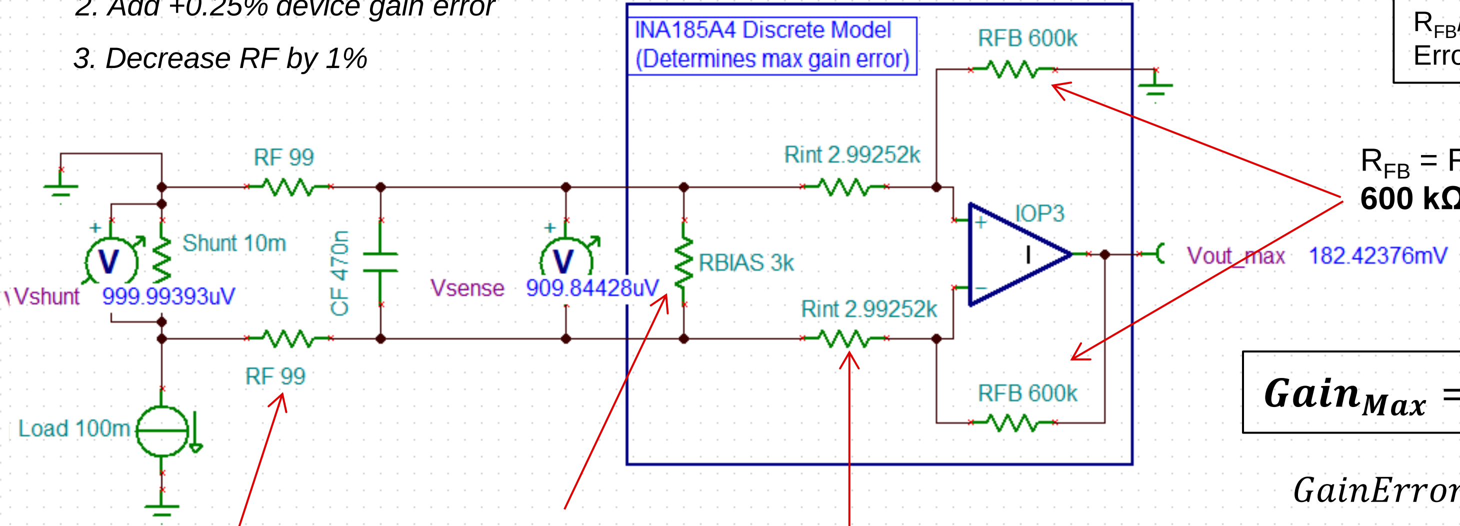
2. Add +0.25% device gain error

3. Decrease RF by 1%

R_{FB}, R_{INT}, and R_{BIAS} all can vary ±20%

R_{FB}/R_{INT} = Gain

R_{FB}/R_{INT} variation = Max Device Gain Error = ±0.25% for INA185A4



$R_{FB} = R_{FB,\ typical}$*(1 + 20%)
600 kΩ = 500 kΩ*(1.20)

$R_{BIAS} = R_{BIAS,\ typical}$*(1 + 20%)
3.00 kΩ = 2.5 kΩ*(1.20)

$R_F = R_{F,\ typical}$*(1-1%)
99 Ω = 100 Ω*(0.99)

$R_{INT} = R_{FB}/[Gain_{Device}$*(1 + 0.25%)]
2.99252 kΩ = 600 kΩ / [200*1.0025]

$$\boldsymbol{Gain_{Max} = \frac{182.424\ mV}{1\ mV} = 182.424\ \frac{V}{V}}$$

$$GainError_{Max} = \frac{Gain_{Max} - Gain_{Typ}}{Gain_{Typ}} * 100$$

$$GainError_{Max} = \frac{182.424 - 178.57}{178.57} * 100$$

$$\boldsymbol{GainError_{Max} = +2.16\%}$$

Example – Determine negative gain error

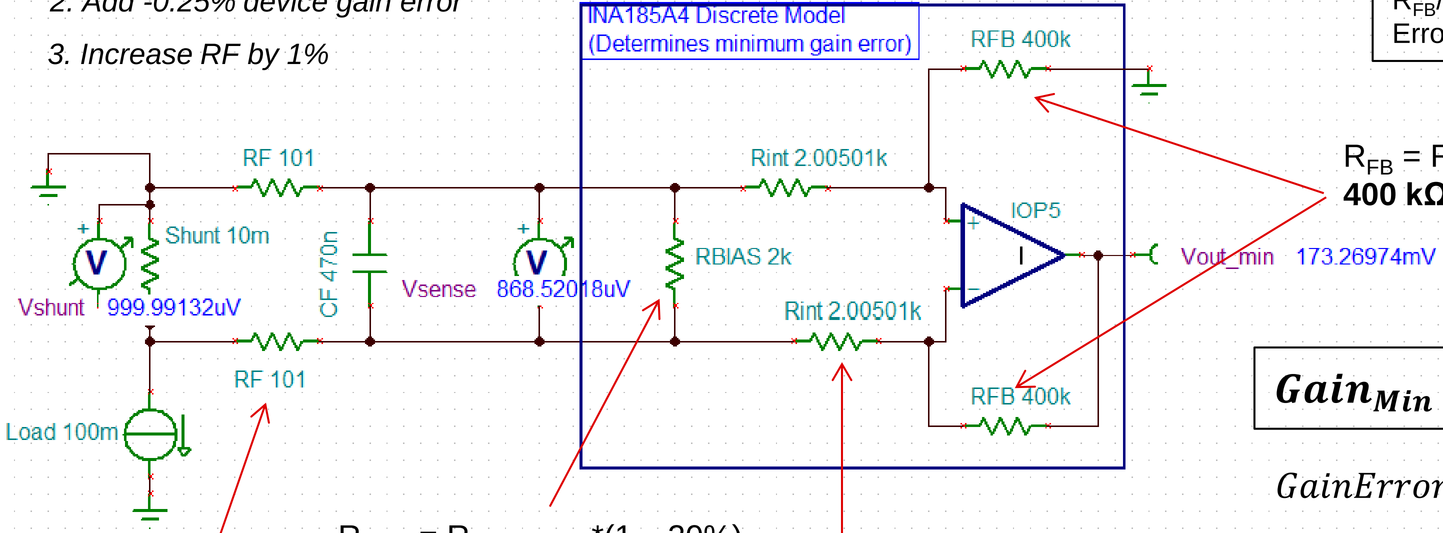
What is smallest possible gain?

1. *Decrease internal resistors by 20%*
2. *Add -0.25% device gain error*
3. *Increase RF by 1%*

R_{FB}, R_{INT}, and R_{BIAS} all can vary ±20%

R_{FB}/R_{INT} = Gain

R_{FB}/R_{INT} variation = Max Device Gain Error = ±0.25% for INA185A4



$R_{FB} = R_{FB,\ typical}*(1 - 20\%)$
400 kΩ = 500 kΩ*(0.80)

$R_{BIAS} = R_{BIAS,\ typical}*(1 – 20\%)$
2.00 kΩ = 2.50 kΩ*(0.80)

$R_F = R_{F,\ typical}*(1+1\%)$
101 Ω = 100 Ω*(1.01)

$R_{INT} = R_{FB}/[Gain_{Device}*(1 - 0.25\%)]$
2.00501 kΩ = 400 kΩ / [200*0.9975]

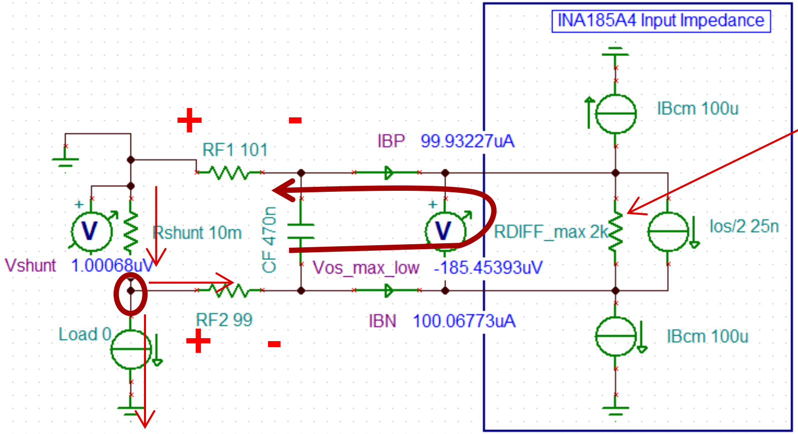
$$\boldsymbol{Gain_{Min} = \frac{173.27\ mV}{1\ mV} = 173.27\ \frac{V}{V}}$$

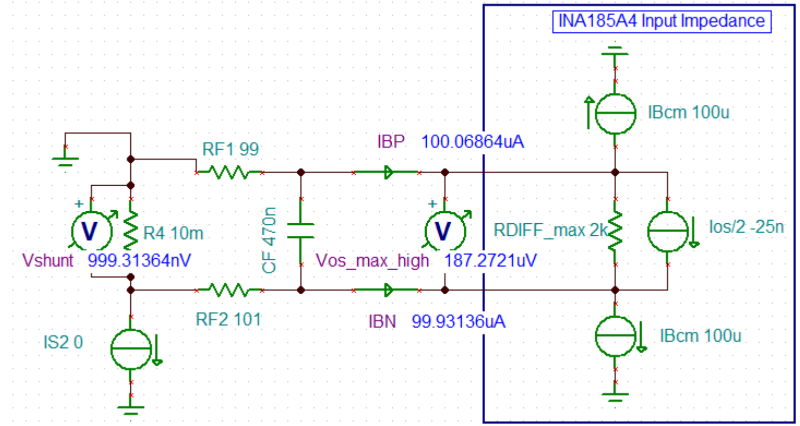
$$GainError_{Min} = \frac{Gain_{Min} - Gain_{Typ}}{Gain_{Typ}} * 100$$

$$GainError_{Min} = \frac{173.27 - 178.57}{178.57} * 100$$

$$\boldsymbol{GainError_{Min} = -2.97\%}$$

Example – Determine new input offset





$$R_{DIFF} = R_{BIAS} || (2 * R_{INT})$$

$$+V_{OS\_Filter} + I_{BP}R_{F1} - I_{SH}R_{SH} - I_{BN}R_{F2} = 0$$

$$+I_{SH} - I_{BN} - I_{LOAD} = 0$$

$$+I_{BP} - I_{DIFF} - IB_{CM} - {I_{OS}}/{2} = 0$$

$$+I_{BN} + I_{DIFF} - IB_{CM} + {I_{OS}}/{2} = 0$$

$$I_{DIFF} = {V_{OS\_FILTER}}/{R_{DIFF}}$$

$$\therefore \boldsymbol{V_{OS\_Filter}} = \frac{\boldsymbol{IB_{CM}(R_{SH} + R_{F2} - R_{F1}) - (\frac{I_{OS}}{2})(R_{SH} + R_{F2} + R_{F1})}}{\boldsymbol{1 + (1/R_{DIFF})(R_{SH} + R_{F2} + R_{F1})}}$$

$V_{OS\_FILTER} \cong \{+187\ \mu V, -185\ \mu V\}$ for $\pm 1\%$ R_F

$$V_{OSI} = \pm 100\ \mu V\ at\ 12 - V\ V_{BUS}$$

$$V_{OS\_CMR} = |12V - V_{BUS}| * 10^{(\frac{-CMRR\_min}{20\ dB})}$$

$$V_{OS\_CMR} = 8V * 10^{(\frac{-106\ dB}{20\ dB})} = \pm 41\ \mu V$$

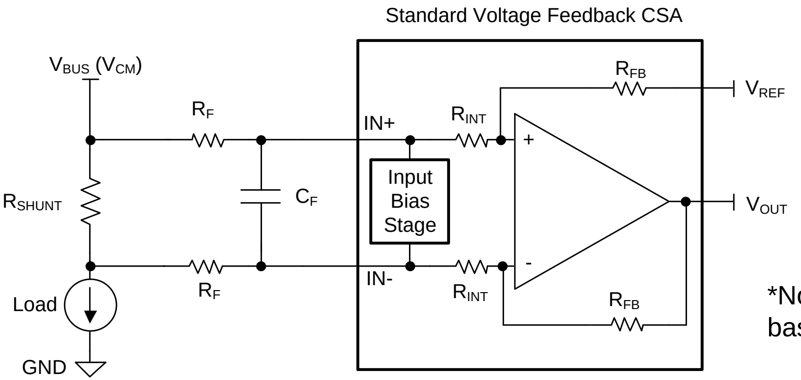
$$V_{OS\_total} = V_{OSI} + V_{OS\_CMR} + V_{OS\_Filter}$$

$$\boldsymbol{V_{OS\_total\_max} = +328\ \mu V}$$

$$\boldsymbol{V_{OS\_total\_min} = -326\ \mu V}$$

Example – Filter error summary

Specification	INA185A4 with no input resistors	INA185A4 with 100-Ω/1% input resistors	INA185A4 with 100-Ω/0.1% input resistors
$V_{OS\_TOTAL\_MAX}$ at 20-V V_{CM}	± 141 µV	+ 328 µV, - 326 µV *(~± 186 µV due to filter)*	+ 165 µV, - 164 µV *(~± 23 µV due to filter)*
Gain (typical)	200 V/V	178.57 V/V	
Gain error (maximum)	± 0.25%	+2.16%, -2.97%	+2.07%, -2.86%

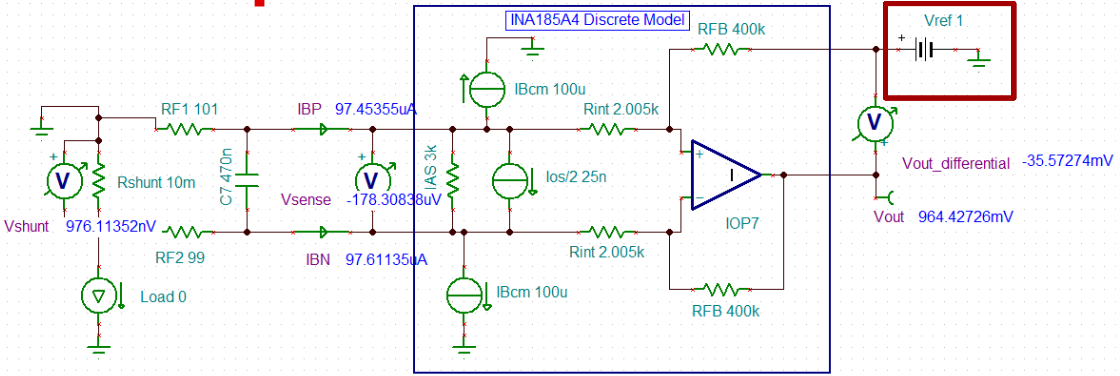


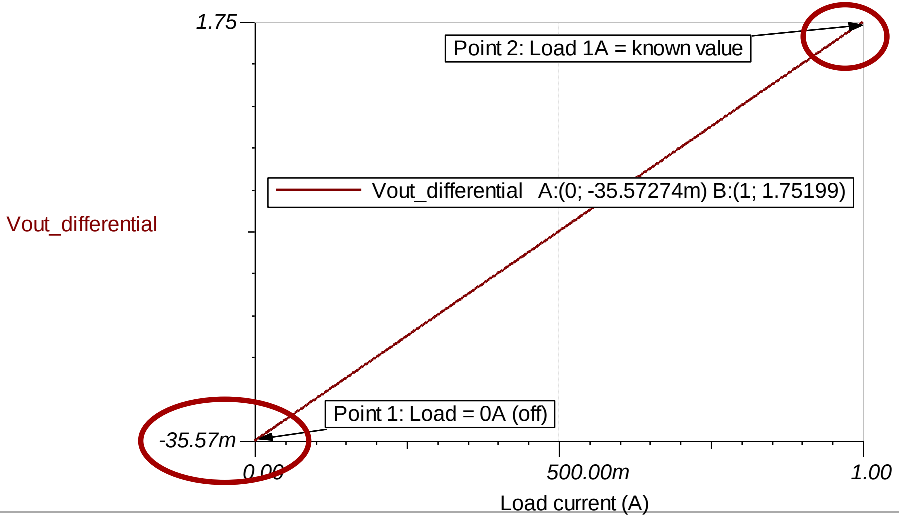
Gain error is dominated by the ± 20% variation* over process in absolute values of R_{FB}, R_{INT}, and R_{DIFF}.

Offset error dominated by R_F tolerance and IB_{CM}.

*Note that the ±20% process variation of R_{FB}, R_{INT}, and R_{DIFF} is a conservative judgment based upon capabilities of the process technology and may differ for other devices.

Example – Calibration





Parameter	Temperature Coefficient
V_{OS}, IB_{CM}, Gain Error	Temperature-stable device specifications. See datasheet.
R_{FB}, R_{INT}, R_{BIAS}	SiCr thin-film resistor process technology. Conservative USL/LSL = ± 30 ppm/°C. All resistors drift with same polarity. ± 30 ppm/°C equates to an additional -0.07%, +0.05% gain error over -40°C to +125°C operating temperature range.
R_F	5 ppm/°C to 25 ppm/°C for majority of thin-film, SMT resistors.

$$V_{OUT\_Calibrated} = \frac{\Delta V_{OUT\_measured}}{\Delta Load_{measured} * Rshunt} * Load + V_{OS_{Output-referred}}$$

$$V_{OUT\_Calibrated} = \frac{1.75199\text{V} - (-0.0355727V)}{1A * 10m\Omega} * Load - 35.5727mV$$

$$V_{OUT\_Calibrated} = 178.756\frac{V}{V} * \text{Load} * 10\text{m}\Omega - 35.5727\text{mV}$$

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Quiz

How to Read CSA Datasheets – quiz

1. Select all of the following that are true about CSAs
   a. Differential input resistances can be in the range of a few kΩ.
   b. Input bias stages require differential input bias currents to partially power the CSA.
   c. Input bias stages require common-mode input bias currents to partially power the CSA.
   d. The internal resistors (RBIAS, RINT, and RFB) can all vary by ±20% due to temperature variation.

How to Read CSA Datasheets – quiz

2. Select all of the following that are true about CSAs with input filters:
   a. Input filters will cause the gain from shunt voltage to device output to be increased.
   b. Input filters will cause the gain error variation to increase.
   c. The offset error due to the input filter will be dominated by the tolerance of the input resistors chosen.
   d. If the input filter capacitor chosen is too large, then the device could become unstable.
   e. The new circuit gain will be dependent upon the common-mode input bias current.

How to Read CSA Datasheets – quiz

3. A system designer needs a CSA with an input filter with 100-Ω input resistors (RF). Which device will yield the lowest input filter error?
    a. The INA190A3 or the INA185A3?

How to Read CSA Datasheets - quiz

4. A system designer is using an input filter for the INA185A4 and decides to calibrate the circuit’s offset and gain error. She notices that error increased unexpectedly when the common-mode voltage level changed from 20-V to 10-V and the temperature was stable. What happened?

Answers

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3. A system designer needs a CSA with an input filter with 100-Ω input resistors (RF). Which device will yield the lowest input filter error?
   a. The INA190A3 or the INA185A3?

Answer: The INA190A3 will yield a lower error due to input filter because it is a high-input impedance CSA with lower input bias currents.

How to Read CSA Datasheets - quiz

4. A system designer is using an input filter for the INA185A4 and decides to calibrate the circuit's offset and gain error. She notices that error increased unexpectedly when the common-mode voltage level changed from 20-V to 10-V and the temperature was stable. What happened?

Answer: The error increased because the common-mode voltage (V_{CM}) was not stable. Once the V_{CM} changes, the IB_{CM} will also change and this affects the input offset voltage due to input filters for CSAs.