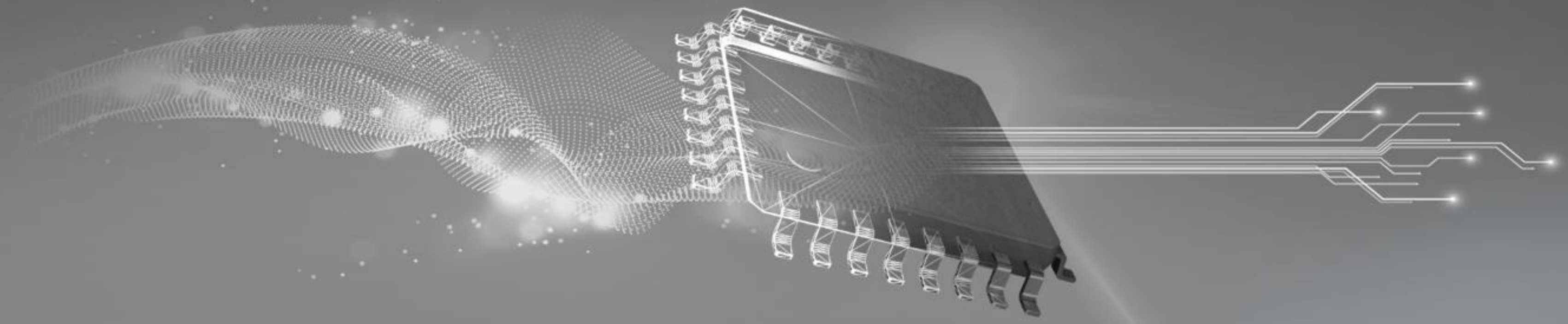
TI TECH DAYS



Calculating and simulating error in current sensing systems

Mubina Toa and Peter Iliya

Current and Position Sensing

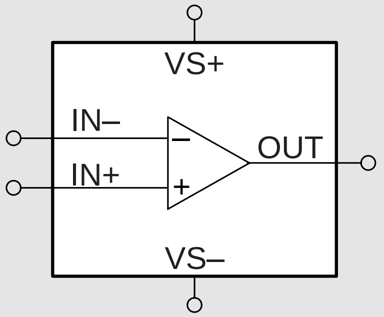
Agenda

- Current sensing architectures (5-7min)
- Error analysis (3 min)
- PSPICE simulation (9 min)
- Key current sensing applications (4 min)
- TI current sensing portfolio (4 min)

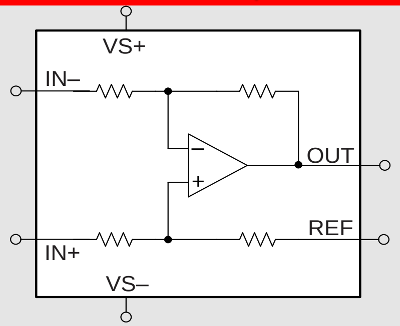
HV capable

Current sensing architectures: types

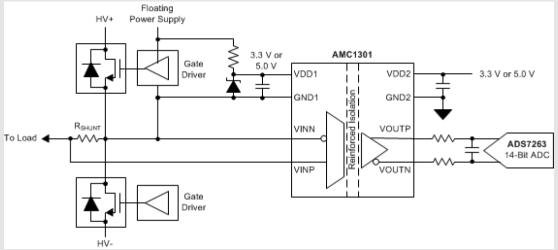
Operational amplifier



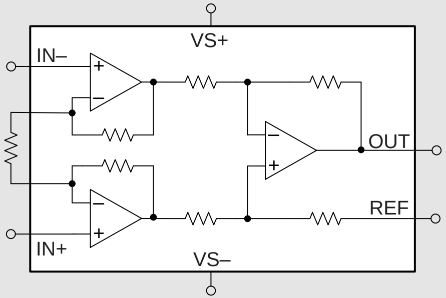
Difference amplifier



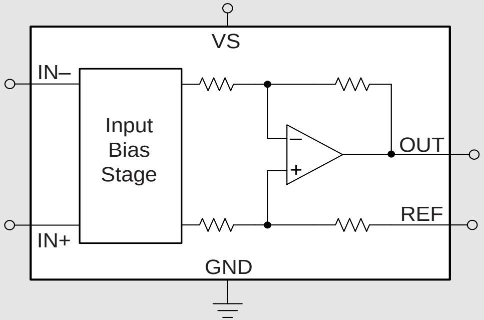
Isolated current sense



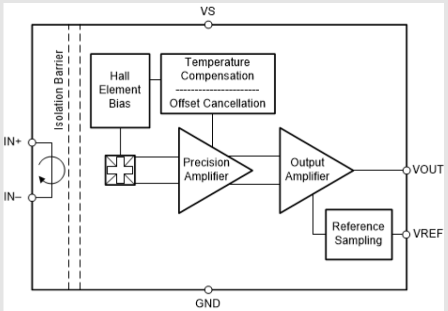
Instrumentation amplifier



Current sense amplifier



In-package Hall-effect current sensor



HV capable

Current sensing architectures: pros and cons

Operational amplifier

Pros

- Large open-loop gain
- Often very low cost

Cons

- Accuracy is set by external components
- Low-side only: VCM ≈ GND
- With a single-ended input, PCB parasitics will create additional error

Difference amplifier

Pros

- Can tolerate very large common-mode voltages (up to ±275V with ±15V supply)

Cons

- System impedance < than diff amp input impedances; Resistor network loads sys.
- Low gain requires additional amplifier stage to keep P_{DIS} in shunt reasonable
- Output must be managed to limit output dynamic range to protect downstream circuitry when supporting high V_{CM}

Isolated current sense

Pros

- Extends CM capability by galvanically isolating the input stage from the output
- Enables galvanic isolation even in low voltage (< 100V) apps w/ transients
- Low offset & integrated precision gain network on input enable high accuracy

Cons

- Limited gain options limit shunt resistor options

Instrumentation amplifier

Pros

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

Cons

- Common-mode voltage must remain within supply voltage, VCM ≤ VS
- Usually used for low-side sensing, but can be used for high-side depending on common-mode voltage

Current sense amplifier

Pros

- Unique floating input stage topology; V_{CM} can exceed and be independent of V_S
- Precision integrated gain network maximizes accuracy and minimizes drift
- Low offset enables use of low ohmic shunt resistors enabling higher current measurements & minimizing power loss

Cons

- Typically only fixed gain

In-package Hall-effect current sensor

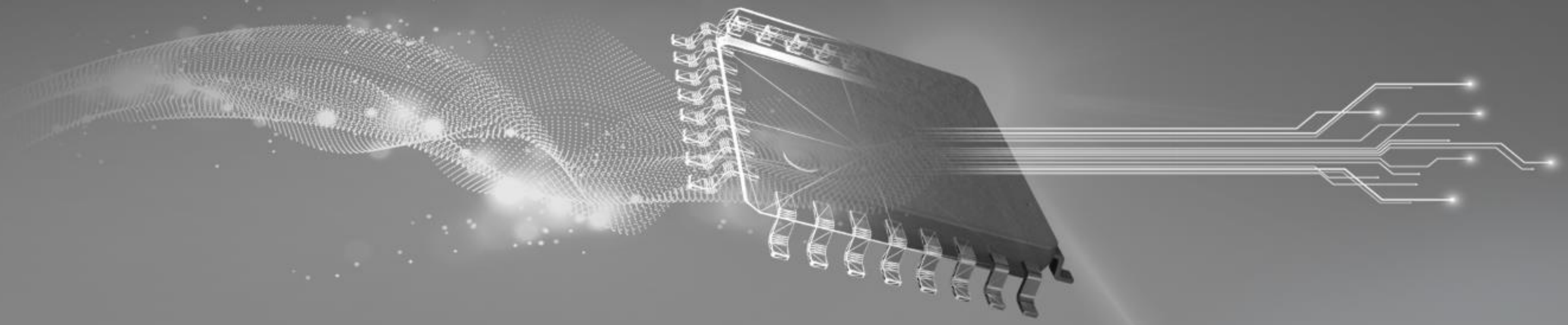
Pros

- Extends common mode capability by galvanically isolating the input stage from the output
- Enables galvanic isolation even in low voltage (< 100V) applications where transients exist that may require isolation

Cons

- Current limited to 30A at 25°C
- Sensitive to stray magnetic fields that can degrade measurement accuracy

TI TECH DAYS



Error analysis (INA228)

Different types of error in current sensing circuits

1. Offset error → $e_{Offset}\ (\%) \approx e_{Vos} + e_{CMRR} + e_{PSRR}$
2. Gain error → $e_{Gain}\ (\%) \approx e_{Gain\_error} + e_{Linearity} + e_{Shunt\_tolerance}$
3. Application error → $e_{Application}\ (\%) \approx e_{Bias\_current} + e_{Other}$

Worst-case total error – more conservative

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

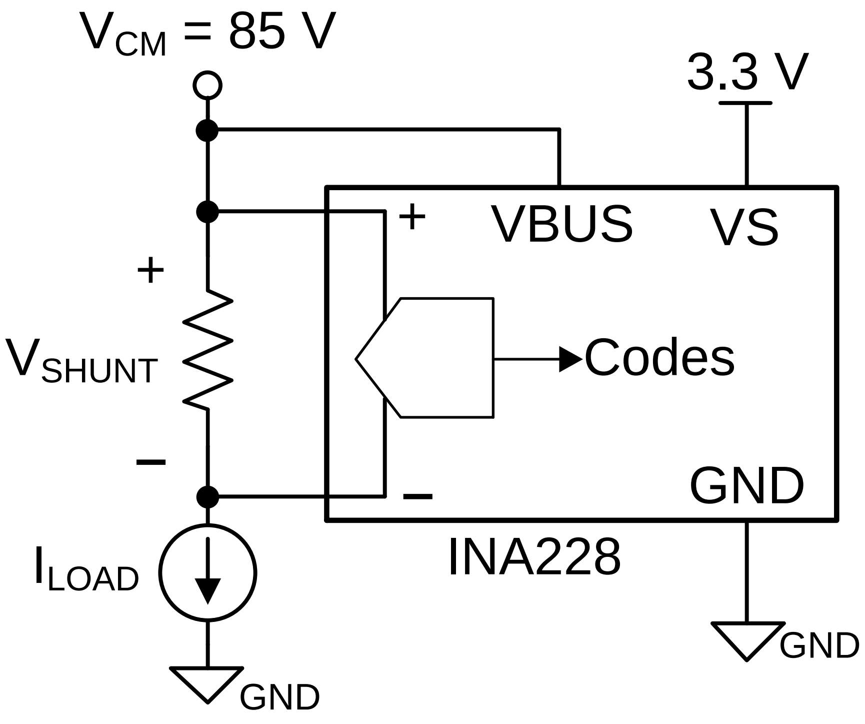
Root-sum-square (RSS) total error – more realistic

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

INA228 error analysis

Conditions

- V_{CM} = 85 V
- VS = 3.3 V
- T_A = 25°C to 120°C (Δ95°C)
- Load = 1 mA to 1 A
- R_{SHUNT} = 100 mΩ
    - V_{SHUNT} = 100 µV to 163 mV
- LSB_V_{SHUNT} = 312 nV (ADCRANGE=0)
- ADC conversion time = 4.12 ms
- ADC number of averages = 512



Note: R_{SHUNT} has perfect 0% tolerance in this example

INA228 error analysis example

- Determine the maximum offset for V_{SHUNT} measurement

$$V_{OSI} = \pm 2\,uV$$

$$V_{OS\_CMRR} = |V_{CM} - 48V| * 10^{-\frac{CMRR_{min}}{20dB}} = |85V - 48V| * 10^{-\frac{146}{20dB}} = \pm 1.85\,\mu V$$

$$V_{OS\_PSRR} = |VS - 3.3V| * PSRR_{min} = 0$$

$$V_{OS\_drift} = |\Delta TA| * \frac{dV_{OS}}{dT} = |95°C| * 0.01\,\frac{\mu V}{°C} = \pm 0.95\,\mu V$$

$$\boldsymbol{V_{OS\_Total} = V_{OSI} + V_{OS_{CMRR}} + V_{OS\_PSRR} + V_{OS\_drift} = \pm 4.8\,\mu V}$$

- Determine the maximum ADC gain error for V_{SHUNT} measurement

$$G_{Error\_25C} = \pm 0.1\% = \pm 0.001$$

$$G_{Error\_drift} = |\Delta TA| * 20ppm = 95°C * 20ppm * 10^{-6} = \pm 0.0019$$

$$\boldsymbol{G_{Error\_total} = G_{Error\_25C} + G_{Error\_drift} = \pm 0.0029}$$

INA228 error analysis example

- Convert to digital codes and calculate total error at 1 mA load

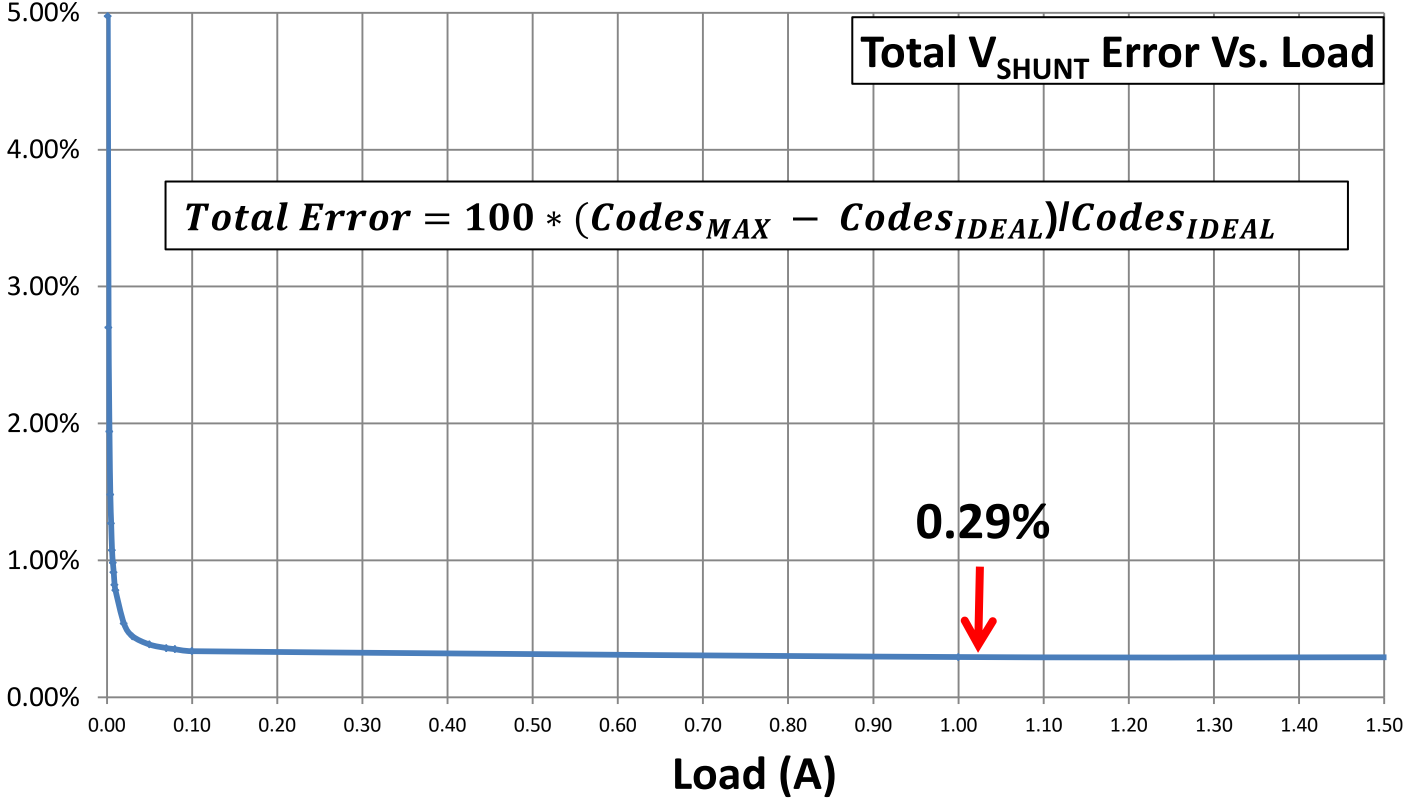
$$G_{IDEAL} = \frac{1}{LSB\_VSHUNT} = \frac{1}{312\ nV} = 3{,}076{,}923\,\frac{codes}{V}$$

$$Codes_{IDEAL\_1mA} = V_{SHUNT} * G_{IDEAL} = 1mA * 100m\Omega * 3{,}076{,}923 = 307.7\ codes$$

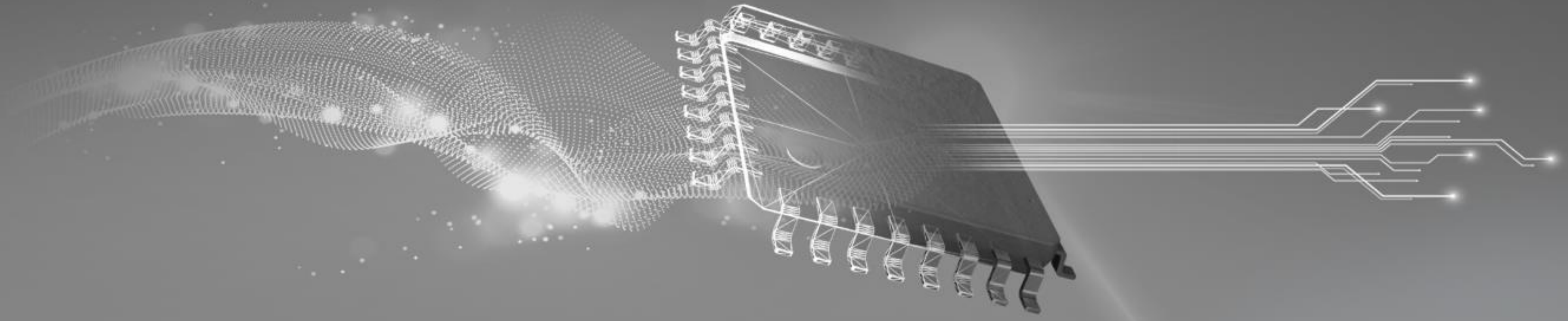
$$Codes_{MAX\_1mA} = ROUND[\ (V_{SHUNT} + VOS) * G_{IDEAL} * \left(1 + G_{Error\_total}\right)] = 323\ codes$$

$$\boldsymbol{Total\ Error\ at\ 1mA = 100 * \left(Codes_{MAX\_1mA} - Codes_{IDEAL\_1mA}\right) / Codes_{IDEAL\_1mA} = 4.98\%}$$

INA228 error analysis example



TI TECH DAYS



PSPICE simulation with INA293

Simulation models for current sense amplifiers (CSA)

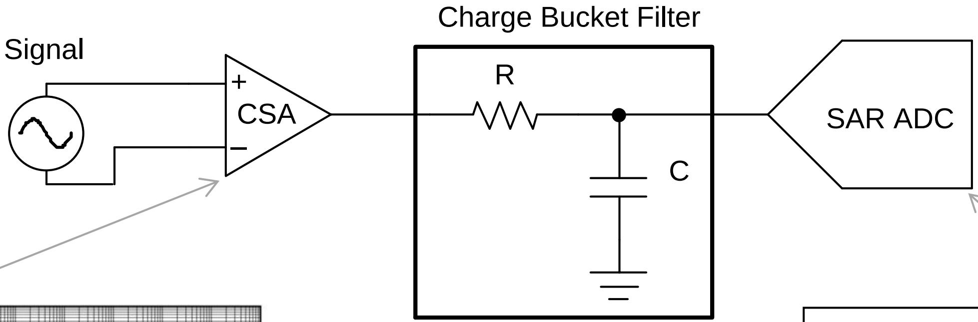
- SPICE models include the following behaviors from datasheet:
  - V_{OS}, gain error, and drift over temperature
  - Input bias and input offset currents
  - Noise density
  - Bandwidth, slew rate
  - Claw curve (Swing-to-rail Versus Output current)
  - AC and DC CMR
  - AC and DC PSR
  - Output impedance (Z_{OUT})
- Most models are behavioral based and not transistor based.
- Models work best for small-signal analyses.

PSpice® for TI

- *In addition to the free TINA-TI software, TI now offers a free simulation and design environment using PSPICE from Cadence.*
- *Includes mixed-signal simulation capability and a full library of pre-loaded models along with links to technical documentation.*

Simulation example - charge bucket filter for ADC

***Problem*: Solve for R and C to yield <1/2 LSB error with SAR ADC.**
***Advantages*:**
- ***Reduce design time.***
- ***Remove need for high-speed buffer amplifier.***



CSA model needs:
→ BW & Z_{OUT}

ADC model needs:
→ Input impedance

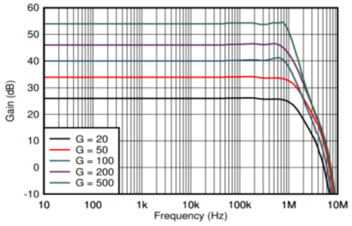


Figure 6-9. Gain vs Frequency

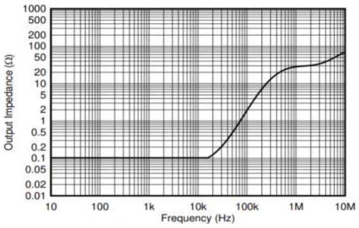
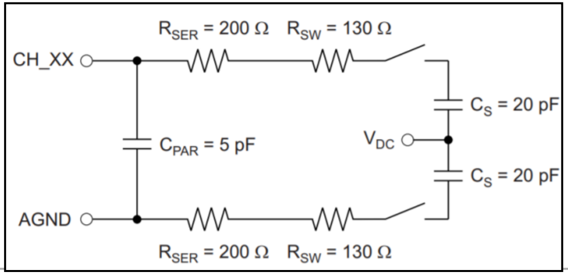
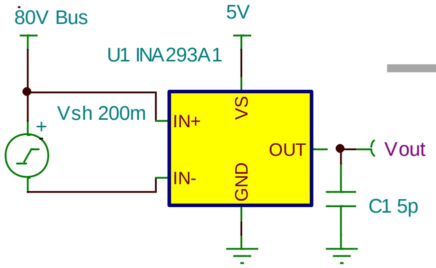
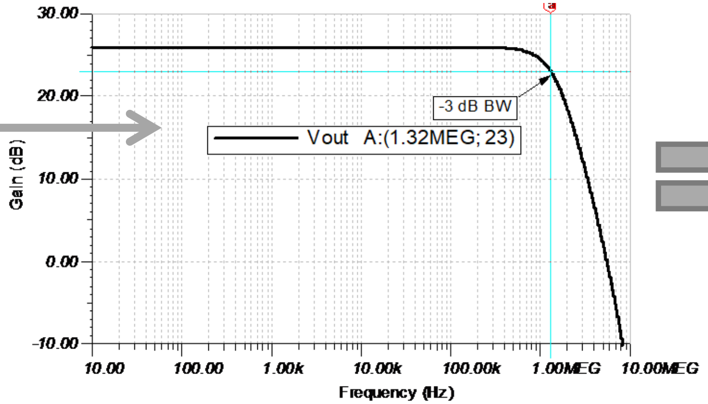


Figure 6-21. Output Impedance vs Frequency



Verify INA293A1 model behavior





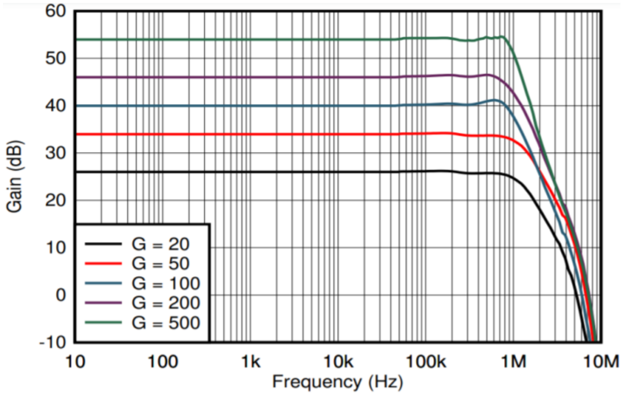
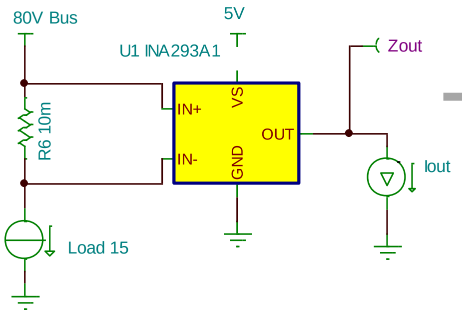
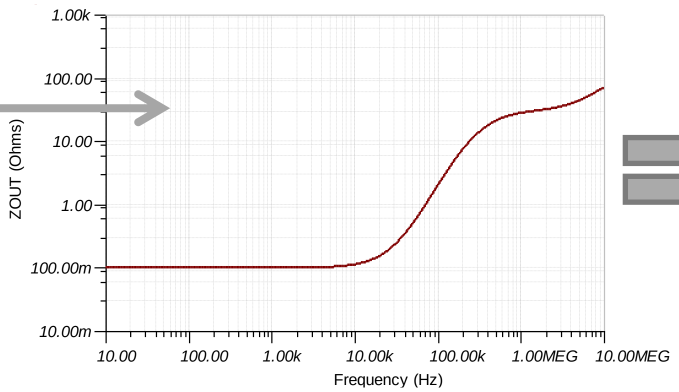


Figure 6-9. Gain vs Frequency





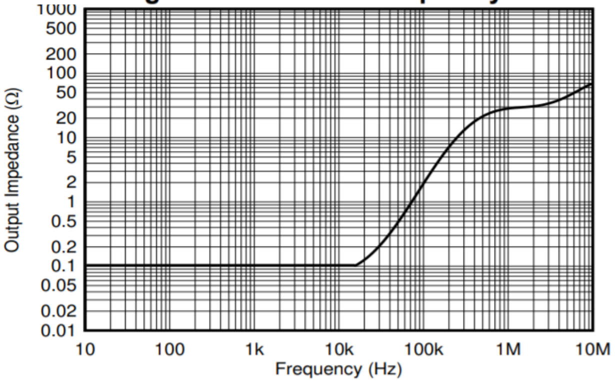
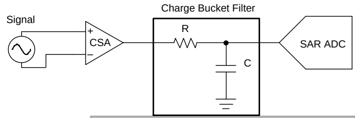
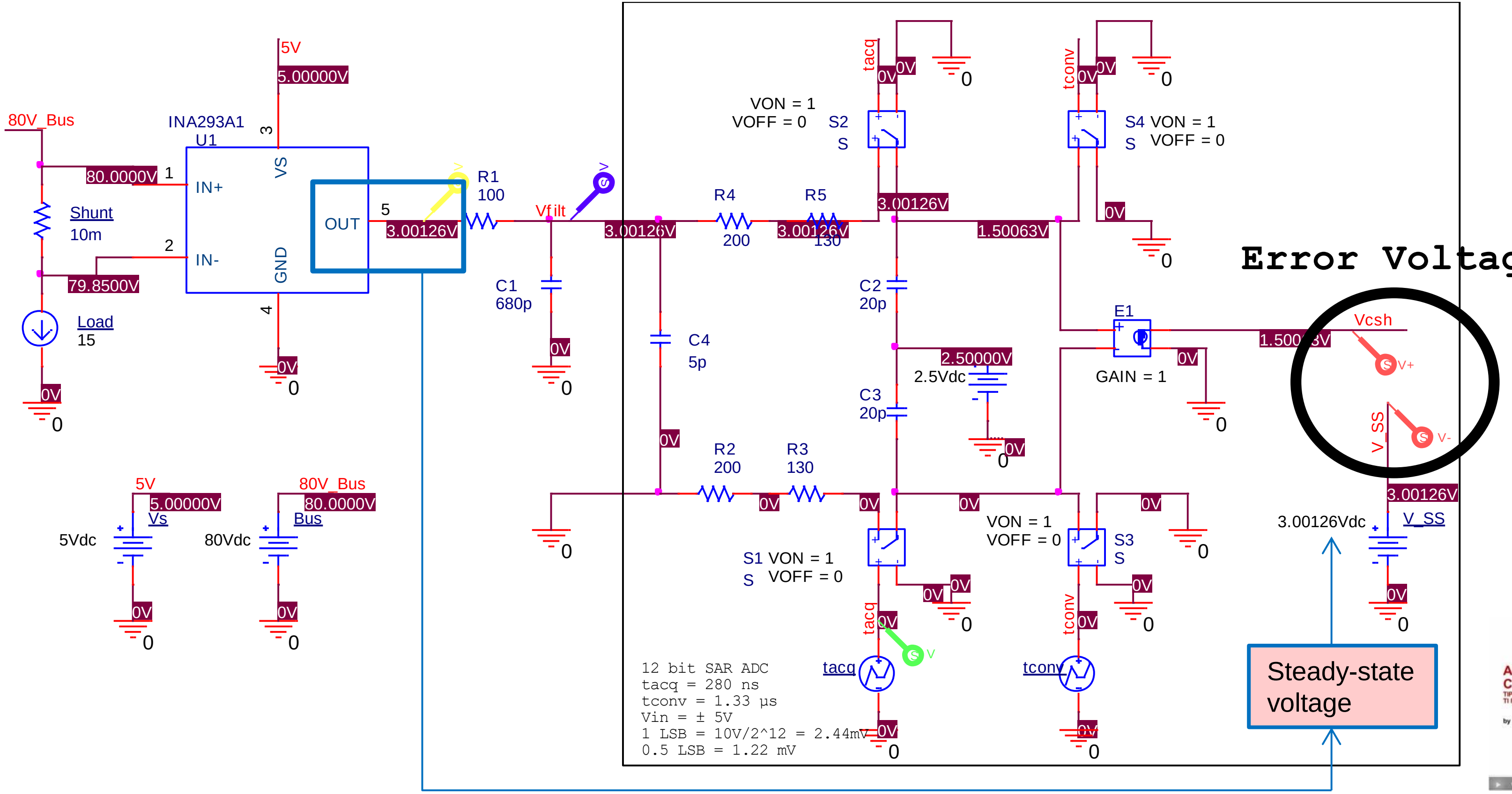


Figure 6-21. Output Impedance vs Frequency

INA293 + ADS8528 with charge bucket

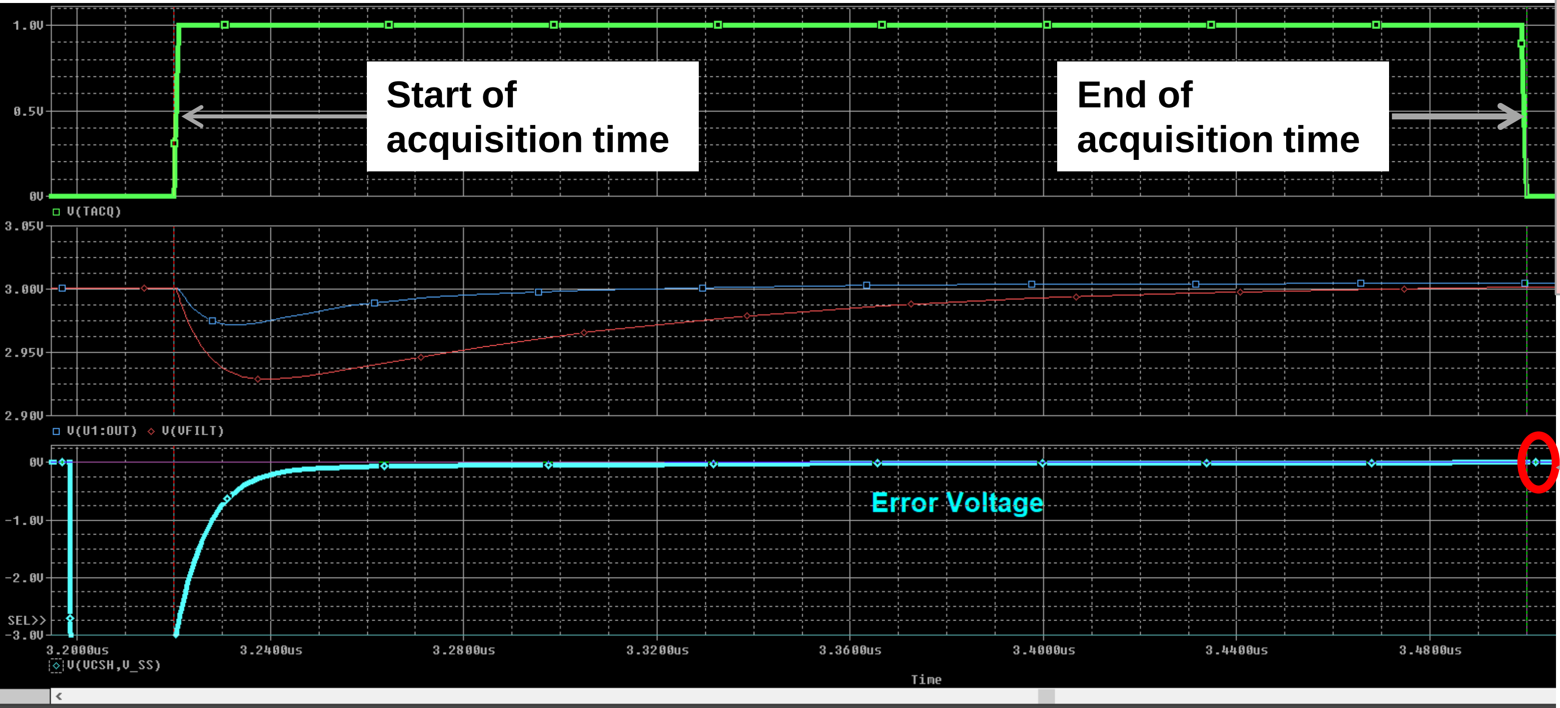


Solve for R and C to yield <1/2 LSB error.



Watch our training videos for more information.

Transient simulation result



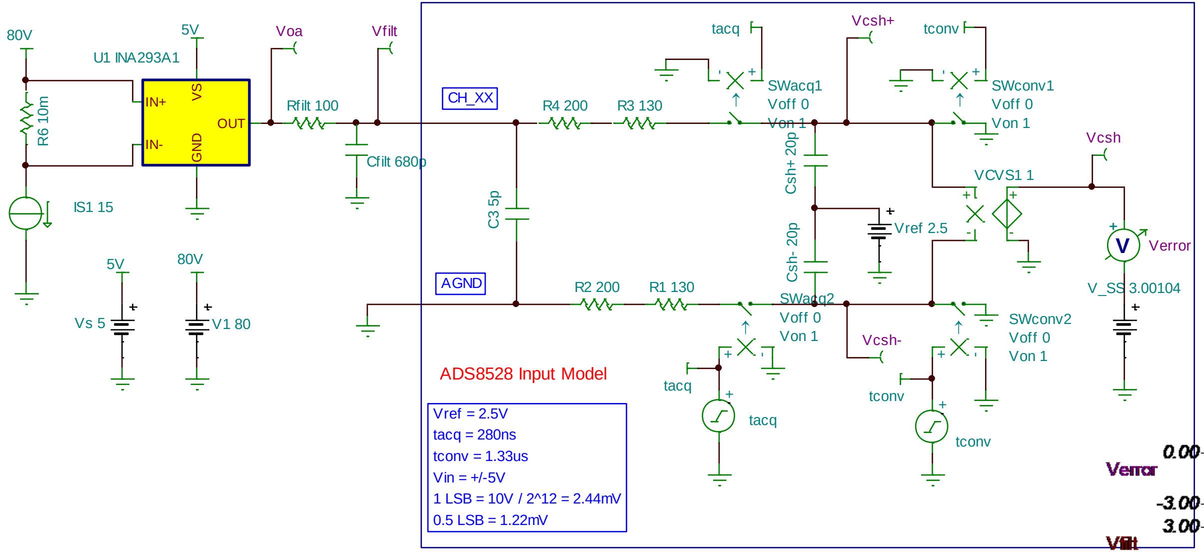
e Cursor

Trace Color	Trace Name	Y1	Y2	Y1 - Y2		Y1(Cursor1) - Y2(Cursor2)		-3.0014		
	X Values	3.2200u	3.5000u	-280.042n		Y1 - Y1(Cursor1)	Y2 - Y2(Cursor2)	Max Y	Min Y	Avg Y
CURSOR 1,2	V(VCSH,V_SS)	-3.0013	150.587u	-3.0014		0.000	0.000	150.587u	-3.0013	-1.5006
	V(U1:OUT)	3.0010	3.0045	-3.4834m		6.0023	3.0044	3.0045	3.0010	3.0028
	V(VFILT)	3.0010	3.0017	-692.992u		6.0023	3.0016	3.0017	3.0010	3.0014
	V(TACQ)	0.000	-120.000n	120.000n		3.0013	-150.707u	0.000	-120.000n	-60.000n

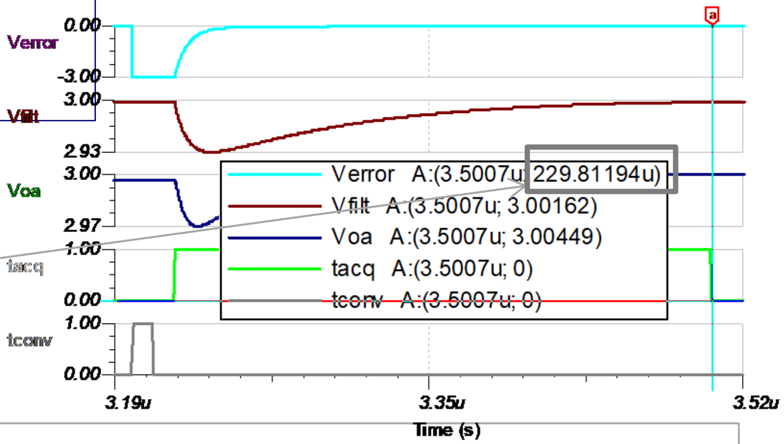
Does the error voltage settle to < 1.22 mV at the end of the acquisition time?

150 µV. Yes, error voltage settles to < 0.5 LSB.

Comparison to TINA-TI



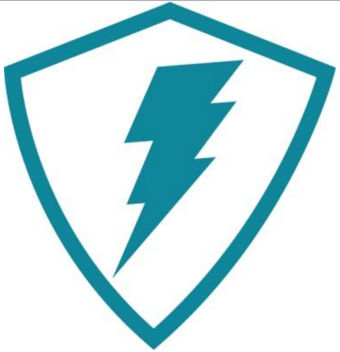
Differences between TINA and PSPICE can arise due to simulation parameter settings.



Verror is 229.8 µV at the end of acquisition time, which satisfies the goal.

Current & power measurement use cases

Solutions customers seek

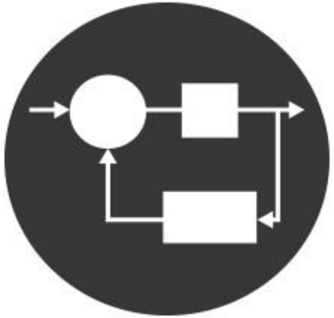


Real-time overcurrent protection (OCP)

Current-level detection exceeding a predetermined threshold as system fluctuations occur due to loads and transients

Current and power monitoring for system optimization

Modeling of system performance and energy to maximize efficiency and/or battery life

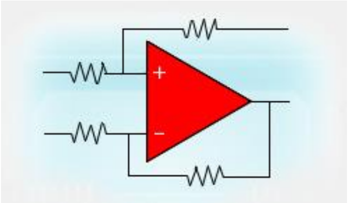


Current measurement for closed loop circuits

Infer diagnostic and/or operational system information from the current measurement

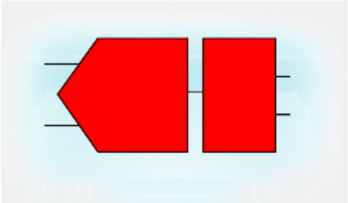
Current sensing portfolio

Analog output



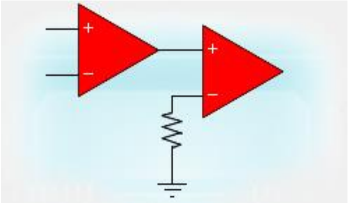
Integrate the full analog signal processing and provide a voltage or current output

Digital monitor



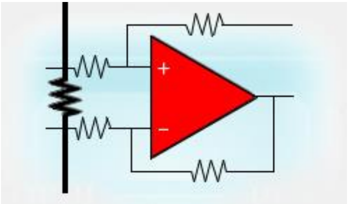
Integrate the full signal conditioning path and utilize standard digital interfaces

Int. comparator



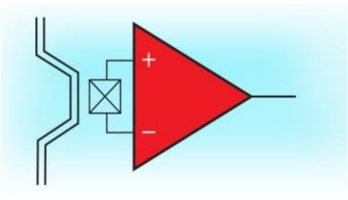
Provides a simple ALERT signal when the load current exceeds a threshold along with analog or digital out

In-package shunt



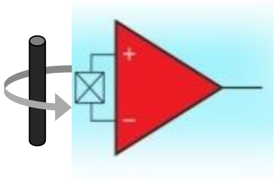
Offers a low-drift, precision shunt resistor element in-package with either analog or digital out

In-package Hall-effect current sensors



Offers precision isolated Hall through-package current measurement.

Ambient magnetic field current sensors



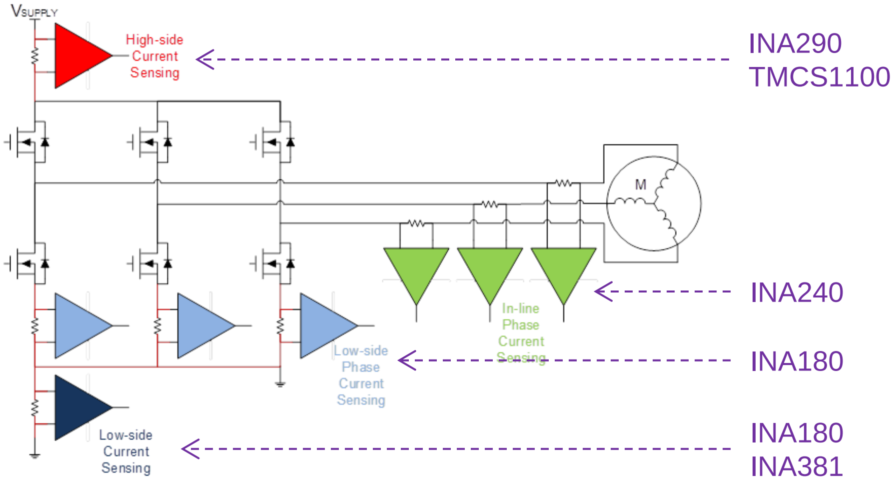
On-chip sensors measures the magnetic field flux density and generates a voltage output proportional to the current

Current sensing use-cases in industrial

Analog current sense amplifier use-cases

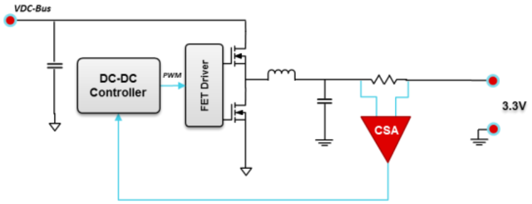
Brushless DC motor commutation

Uses up to three current sense amplifiers in low-side of high-side configurations for torque measurement.



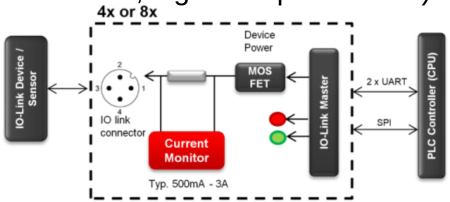
Power supplies

Current sensing in power supplies for accurate current measurement for control loops and quick over-current detection.



PLCs

To avoid that a sensor could create problems for the system, each port monitors the current to ensure proper operation. (Stand-alone remote IO, digital output module)



Low-cost hero devices

Existing
New Release
In Preview
Q100 Option Available
Q100 in Development

Analog output

<48V

INA180/2180/4180
-0.3V to 26V CMR
150uV Offset, 1% Gain Error
Gains: 20, 50, 100, 200 V/V
Op-amp footprint compatible
Single/Dual/Quad options

≥48V

INA281
-4V to 110V CMR
-20V to 120V Survivability
150µV Offset , 0.5% Gain Error
1.3MHz BW & 2.5V/µs slew rate
Gains: 20, 50, 100, 200, 500V/V
SOT-23 Dual Pinouts

INA280
2.7V to 120V CMR
-20V to 122V Survivability
150µV Offset , 0.5% Gain Error
1.1MHz BW & 3V/µs slew rate
Gains: 20, 50, 100, 200, 500V/V
SC-70

Digital monitor

INA237
-0.3V to 85V CMR
50uV Offset & 0.3% Gain Error
16-bit ADC
I2C Output

Integrated comparator

INA381
-0.3V to 26V CMR
500µV Offset, 1% Gain Error
5µs Response Time

High performance hero devices

- Existing
- New Release
- In Preview
- Q100 Option Available
- Q100 in Development

Analog output

<48V

INA190
- -0.1V to 40V CMR
- 15uV Offset , 0.2% Gain Error
- Gains: 25, 50, 100, 200, 500 V/V
- Disable Pin (QFN & SOT23-8)
- SC70-6, QFN-10, & SOT23-8

≥48V

In-line

INA240
- –4.0V to 80V CMR
- 25uV Offset, 0.2% Gain Error
- Gains: 20, 50, 100 V/V
- Enhanced PWM Rejection
- AEC-Q100 Grade 0 in SOIC
- TSSOP & SOIC

High-side

INA290
- 2.7V to 120V CMR
- -20V to 122V Survivability
- 12µV Offset , 0.1% Gain Error
- 1.1MHz BW & 3V/µs slew rate
- Gains: 20, 50, 100, 200, 500V/V
- SC-70

Digital monitor

<48V

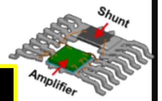
INA226
- 0V to +36V CMR
- 10uV Offset & 0.1% Gain Error
- MSOP-10

≥48V

INA228
- 0V to +85V CMR
- 1uV Offset & 0.1% Gain Error
- 20-bit ADC
- I2C Output

INA229
- 0V to +85V CMR
- 1uV Offset & 0.1% Gain Error
- 20-bit ADC
- SPI Output

Integrated shunt



INA250
- 0.75% total gain error over temp
- –0.3V to 36V CMR
- Available Gains: 200, 500, 800, 1000 mV/A
- TSSOP-16

INA253
- 0.75% total gain error over temp
- –4.0V to +80V CMR
- Gains Options: 200, 500, 1000 mV/A
- TSSOP-16

TMCS1100

Precision, bi-directional, galvanically isolated current sensor with external reference

Features

- 80 kHz signal bandwidth.
- 1% accuracy (-40 to 125°C).
- ±600 V working voltage, 3 kV dielectric isolation (IEC 60950-1).
- Operating voltage: 3.0 V to 5.5 V.
- 20 A max continuous DC/RMS current (thermally limited).
- Multiple sensitivities for wide linear measurement ranges:
  - TMCS1100A1: 50 mV/A – TMCS1100A2: 100 mV/A
  - TMCS1100A3: 200 mV/A –TMCS1100A4: 400 mV/A
- 8-pin SOIC package.
- *AEC-Q100 Grade 1 Option.*

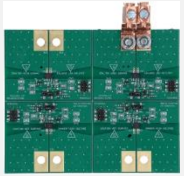
Benefits

- Ability to measure an isolated ac or dc current.
- In-package sensing simplifies PCB and application design.
- Highest accuracy Hall current sensing device in the industry.
- Highest working voltage isolation (600 V) in 8-pin SOIC.
- Ability to precisely set the reference voltage (VREF) independent of Vcc enables higher accuracy.
- VREF can be shared with ADC for increased system accuracy.
- Fixed sensitivity eliminates ratiometry errors and improves supply noise rejection.

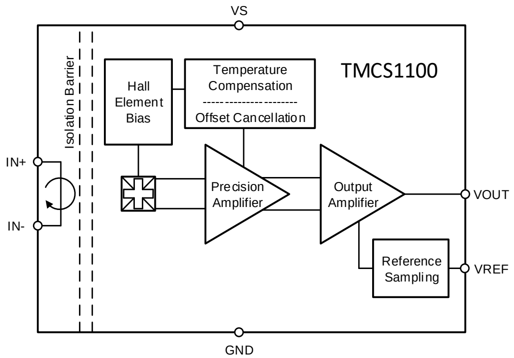
Applications

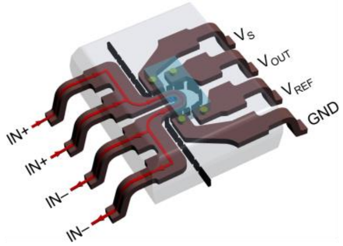
- Motor control
- PV string inverters
- Switching converters
- Overcurrent protection
- Power monitoring
- On-board charger PFC

Tools & Resources

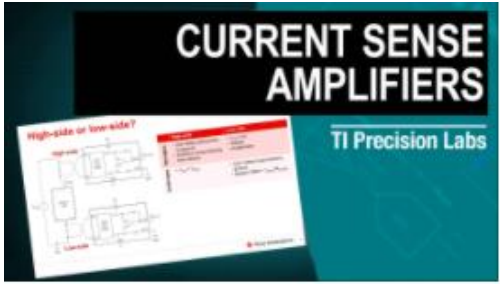


- TMCS1100EVM
- TINA–TI SPICE Model

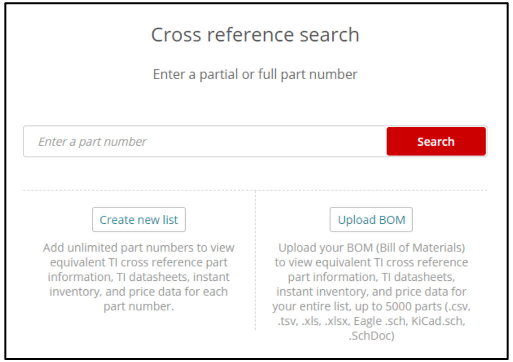




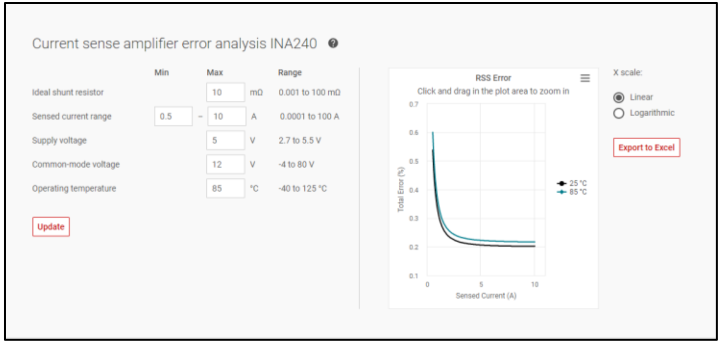
Key Resources



TI Precision Labs



Cross-reference search



Web-based error tool

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