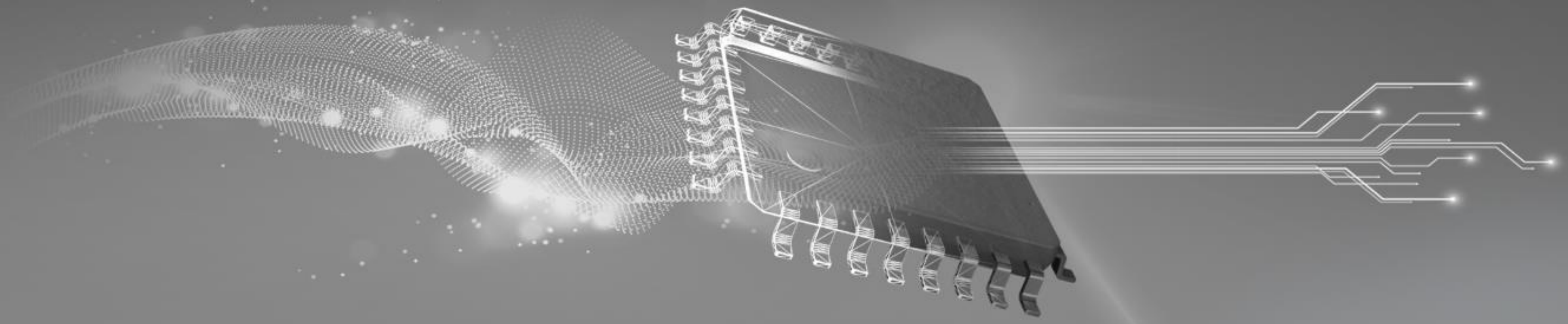
TI TECH DAYS



Precisely measuring current in 48-V vehicles

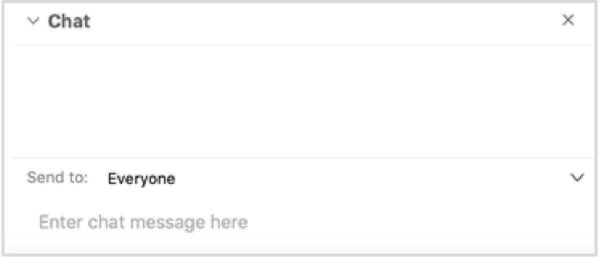
Dan Harmon

Current and Position Sensing

Agenda

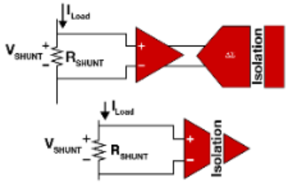
- TI Current Sensing Solutions
- 48V Current Sensing Alternatives
- Automotive 48V Applications
- Key 48V Current Sense Devices

Use the Webex Chat



TI Current Sensing Solutions

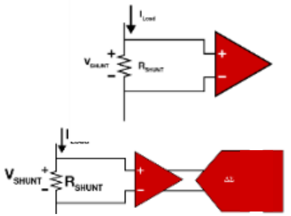
Shunt-based Solutions

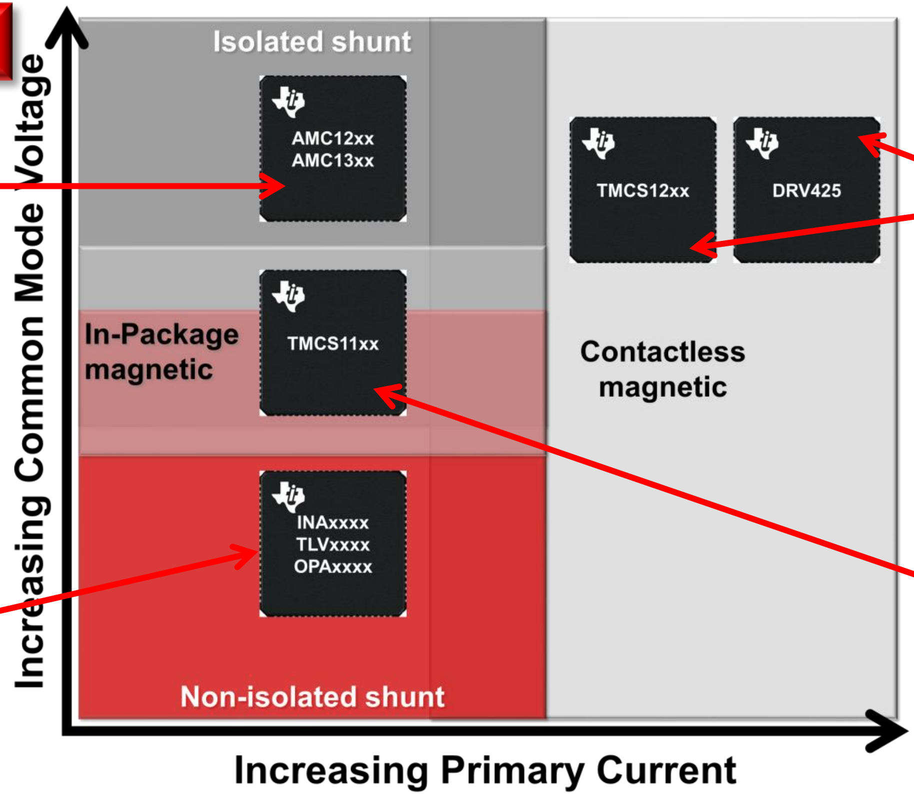


Isolated Options

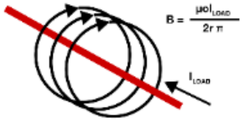
Directly measures the current through a relatively small ohmic valued (shunt) resistor.

Non-Isolated Options



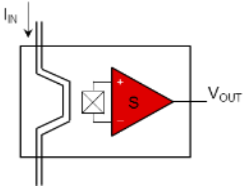


Magnetic Solutions



Non-invasive & Isolated

Magnetic sensing indirectly measures the load current by measuring the magnetic field produced by a current running through a conductor.



Hybrid EV, Battery EV Current Sensing

DC-DC Converter

Power Stage Devices

- 12V Rail:
  ⇨ **INA190-Q1**
- 48V Rail:
  ⇨ **INA240-Q1**
- HV Rail:
  ⇨ **DRV425-Q1**
  ⇨ **AMC1302-Q1**
- Low-side monitoring:
  ⇨ **INA181-Q1**
  ⇨ **INA381-Q1 (OC)**

Diagnostic Devices

- 12V Systems:
  ⇨ **INA186-Q1**
- 48V Systems:
  ⇨ **INA281-Q1**
- HV Systems:
  ⇨ **DRV425-Q1**
  ⇨ **AMC1302-Q1**
- Low-side monitoring:
  ⇨ **INA181-Q1**
  ⇨ **INA381-Q1 (OC)**

Battery Management

State of Charge Devices

- Bottom of Stack:
  ⇨ **INA229-Q1**
  ⇨ **INA226-Q1**
- 12V Battery Top of Stack:
  ⇨ **INA190-Q1**
  ⇨ **INA226-Q1**
- 48V Battery Top of Stack:
  ⇨ **INA240-Q1**
  ⇨ **INA229-Q1**
- HV Battery Top of Stack:
  ⇨ **AMC1302-Q1**
  ⇨ **DRV425-Q1**

Diagnostic Devices

- Low-side:
  ⇨ **INA181-Q1**
  ⇨ **INA381-Q1 (OC)**
- 12V High-side:
  ⇨ **INA186-Q1**
- 48V High-side:
  ⇨ **INA281-Q1**
- HV High-side:
  ⇨ **AMC1302-Q1**
  ⇨ **DRV425-Q1**

On-board Charging

AC Current

- In-package Hall current sensor
  ⇨ **TMCS1100-Q1**

PFC Current

- High-side
  In-package Hall current sensor
  ⇨ **TMCS1100-Q1**
  Shunt monitoring
  ⇨ **AMC1302-Q1**
- Low-side Shunt monitoring:
  ⇨ **INA181-Q1**
  ⇨ **INA381-Q1 (OC)**

DC/DC Current

- HV Monitoring:
  In-package Hall current sensor
  ⇨ **TMCS1100-Q1**
  Shunt monitoring
  ⇨ **AMC1302-Q1**
- Low-side monitoring:
  ⇨ **INA181-Q1**
  ⇨ **INA381-Q1 (OC)**

Traction Inverter/ Motor Control

Motor Current

- In-line phase current requires the ability to negate high dV/dT V_{CM}:
  48V ⇨ **INA240-Q1**
  HV ⇨ **AMC1302-Q1**
- Low-side phase may require negative V_{CM} survivability:
  ⇨ **INA181-Q1**
  ⇨ **INA303-Q1**
  ⇨ **INA281-Q1**

Diagnostic Devices

- Low-side DC-Link:
  ⇨ **INA181-Q1**
  ⇨ **INA381-Q1 (OC)**
- 48V High-Side DC-Link:
  ⇨ **INA281-Q1**
- High-side DC-Link requiring isolation:
  ⇨ **AMC1302-Q1**
  ⇨ **DRV425-Q1**

Starter / Generator

Motor Current

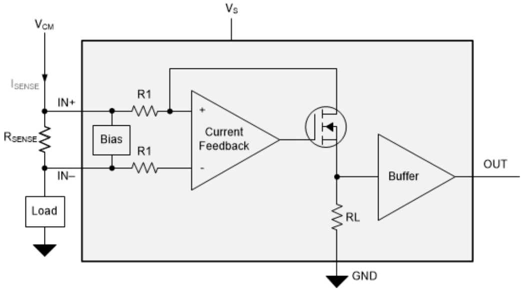
- In-line phase current requires the ability to negate high dV/dT V_{CM}:
  ⇨ **INA240-Q1**
- Low-side phase may require negative V_{CM} survivability:
  ⇨ **INA181-Q1**
  ⇨ **INA303-Q1**
  ⇨ **INA281-Q1**

Diagnostic Devices

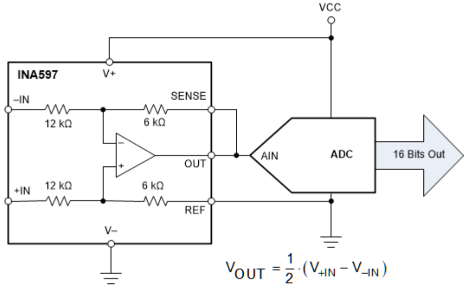
- Low-side DC-Link:
  ⇨ **INA181-Q1**
  ⇨ **INA381-Q1 (OC)**
- 12V High-side DC-Link:
  ⇨ **INA186-Q1**
- 48V High-Side DC-Link:
  ⇨ **INA281-Q1**
- 48V Isolated Systems
  ⇨ **AMC1302-Q1**

48V current sensing options: architecture

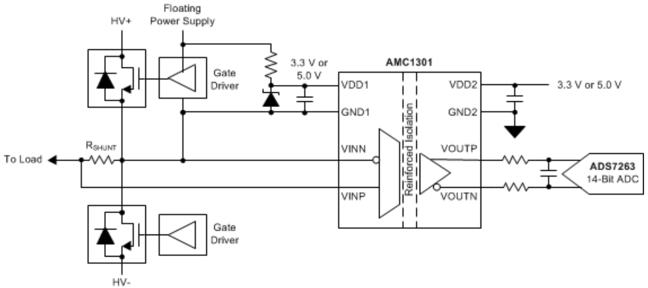
Current sense amplifier



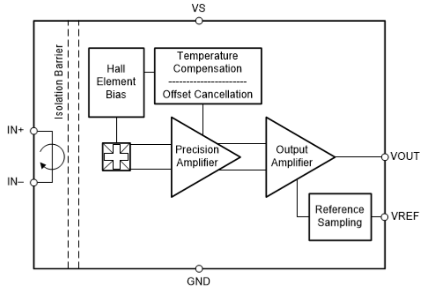
Difference amplifier



Isolated current sense amplifier



In–package Hall–effect current sensor



48V current sensing options: pros & cons

Current sense amplifier

Pros

- Unique floating input stage topology allows for V_{CM} to 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 and minimizing power dissipations

Cons

- Usually only offered at fixed gain options

Difference amplifier

Pros

- Tolerates large common-mode voltages (up to ±275V with ±15V supply)

Cons

- Resistor network loads the system; Must ensure system impedance is significantly smaller than diff amp input impedances
- Typically 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 amplifier

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
- Low offset and integrated precision gain network on input stage enable high accuracy

Cons

- Limited gain options limit shunt resistor options

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

Errors 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 → $e_{Application}\ (\%) \approx e_{Bias\_current} + e_{Other}$

For more info
Click to visit

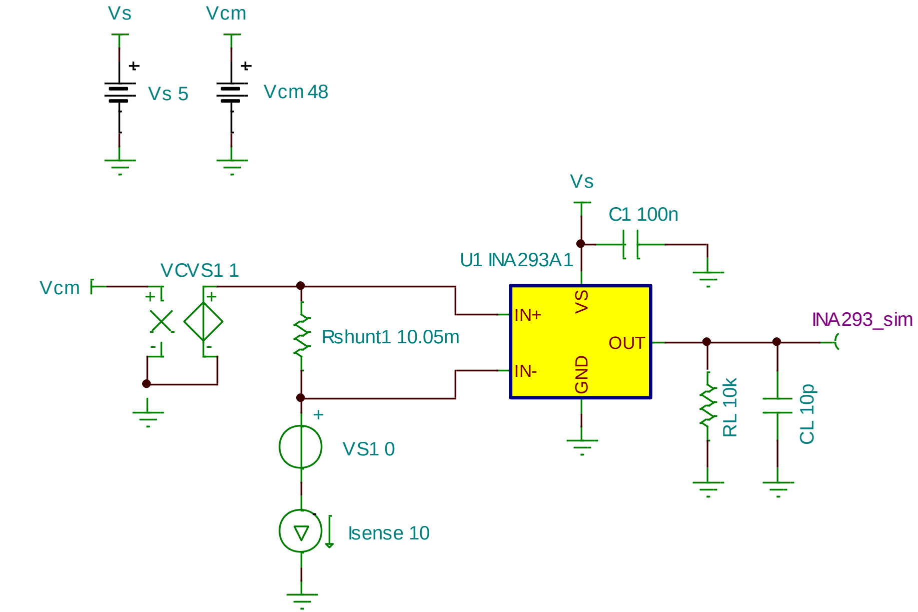
Worst-case total error – more conservative

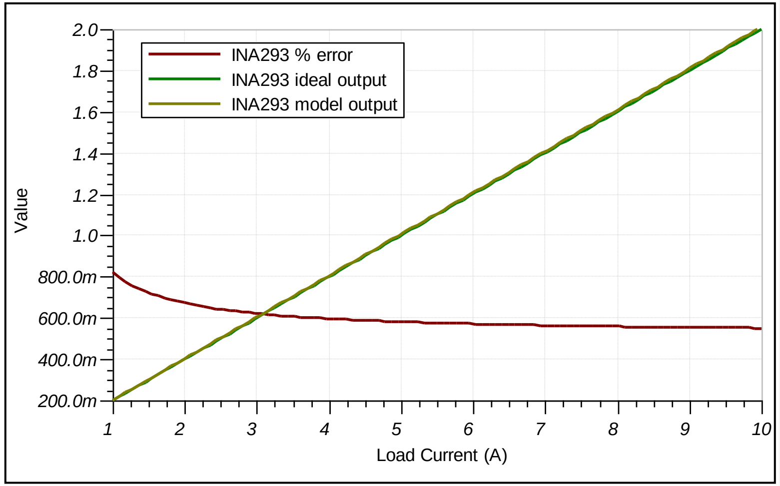
$$\varsigma_{Worst}(\%) \approx e_{Vos} + e_{CMRR} + e_{PSRR} + e_{Gain\_error} + e_{Linearity} + e_{Shunt\_tolerance} + e_{Bias\_current} + e_{Other}$$

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

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

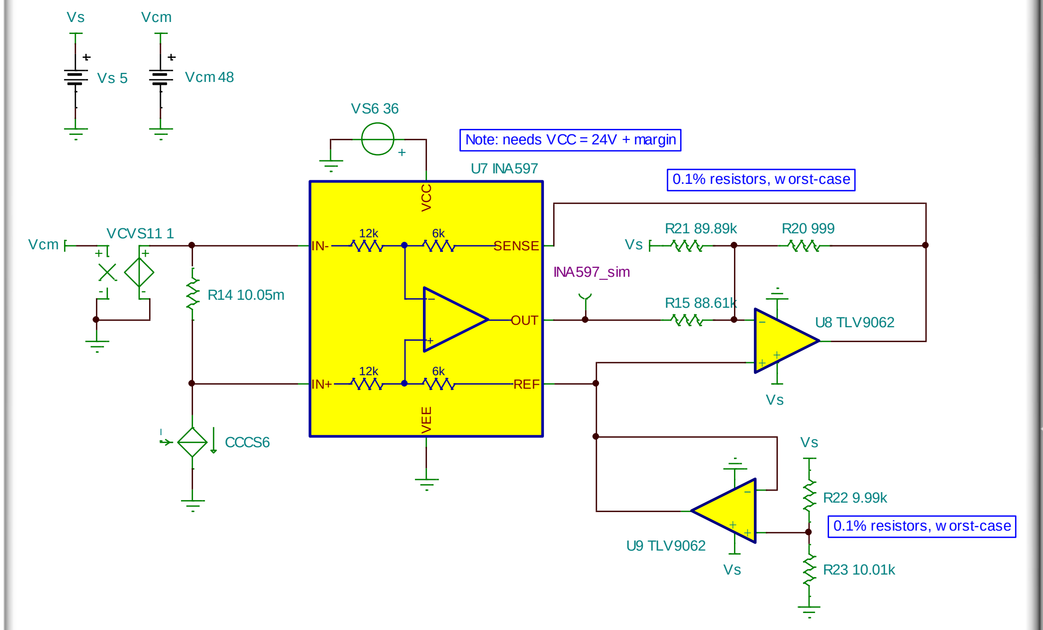
Current sense amplifier option – INA293

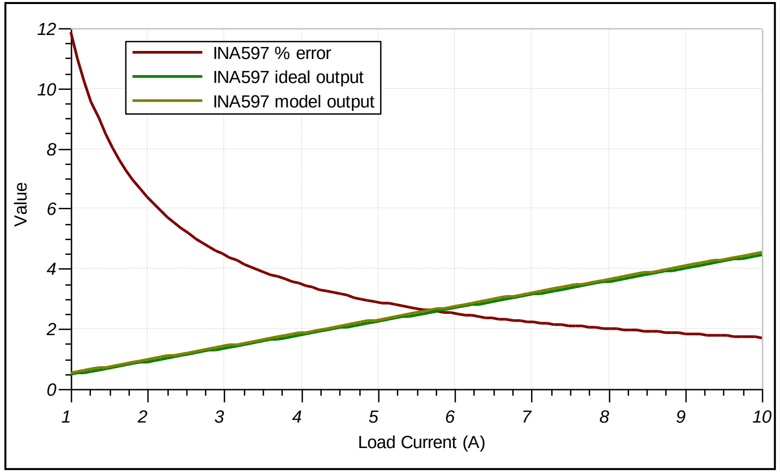




BOM Estimate	INA293
Device	$1.05
Shunt resistor	$0.73
Total cost with 0.5% shunt:	**$1.78**
Item	**Price source**
TI devices	ti.com 1k price
Shunt resistor: 10mΩ, 0.5%, 50 PPM, 1W 2412	Digi-Key 1Ku T&R price

Difference amplifier option – INA597

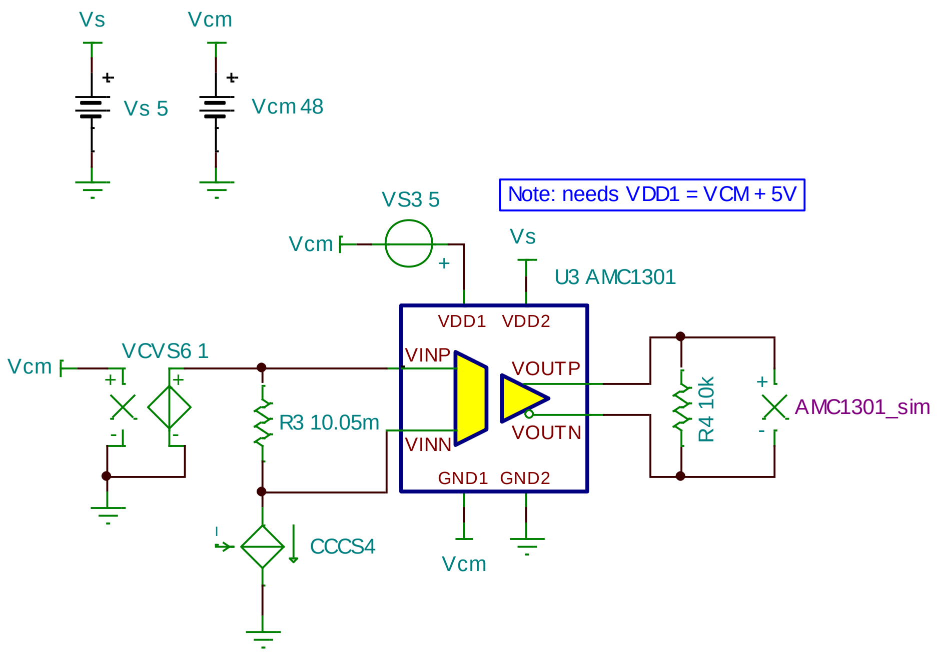


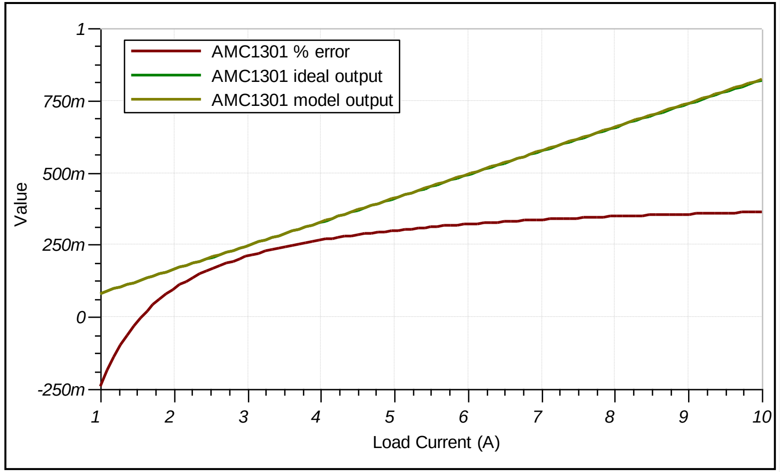


BOM Estimate	INA597		
Device	$0.84		
Shunt resistor	$0.73		
Increase gain stage: TLV9062	$0.25		
	1%	0.5%	0.1%
Total for five of these resistors	$0.08	$0.13	$0.18
Total cost with 0.5% shunt:	**$1.90**	**$1.95**	**$2.00**

Item	**Price source**
TI devices	ti.com 1k price
Shunt resistor: 10mΩ, 0.5%, 50 PPM, 1W 2412	Digi-Key 1Ku T&R price
1%, 100 PPM, 0.25W resistor	Digi-Key 1Ku T&R price
0.5%, 50 PPM, 0603 resistor	Digi-Key 1Ku T&R price
0.1%, 10 PPM, 0.25W resistor	Digi-Key 1Ku T&R price

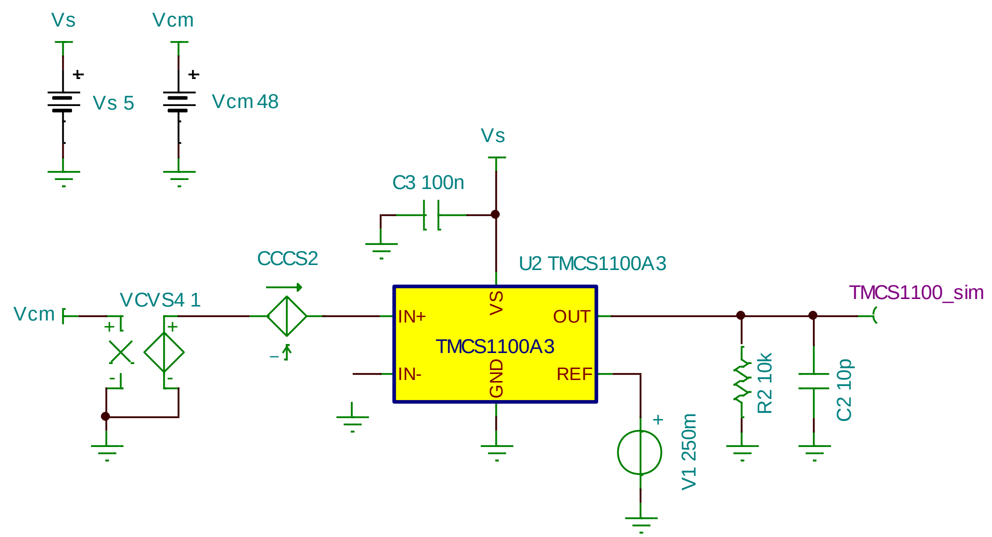
Isolated amplifier option – AMC1301

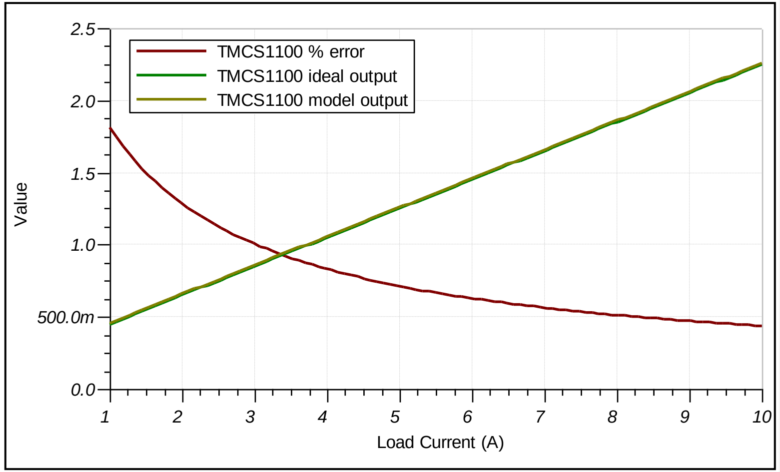




BOM Estimate	AMC1301
Device	$2.55
Shunt resistor	$0.73
Total cost with 0.5% shunt:	$3.28
Item	**Price source**
TI devices	ti.com 1k price
Shunt resistor: 10mΩ, 0.5%, 50 PPM, 1W 2412	Digi-Key 1Ku T&R price

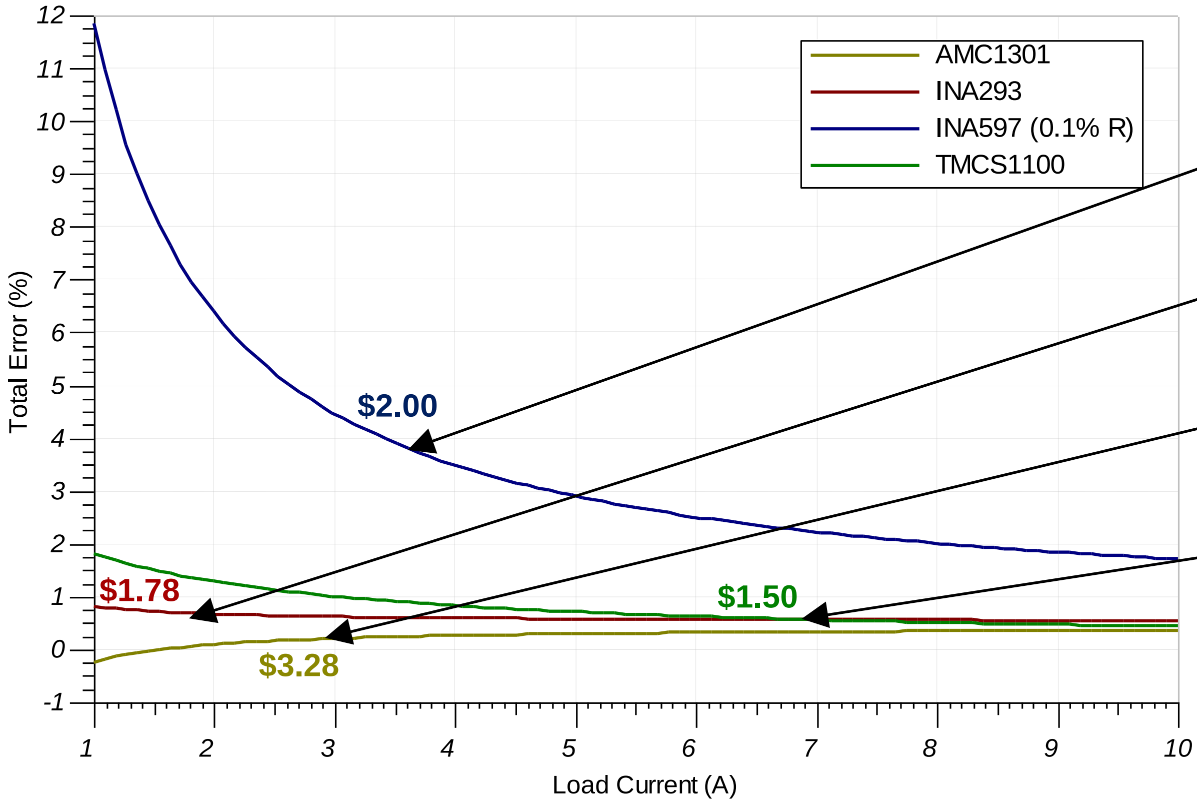
In-package Hall sensor option – TMCS1100





BOM Estimate	TMCS1100
Device	$1.50
Shunt resistor	$0.00
Total cost with 0.5% shunt:	$1.50
Item	Price source
TI devices	ti.com 1k price

48V current sensing options: DC error analysis



Note: TI SPICE models are usually designed to typical specs

DA = poor performance versus price, 2-chip solution

CSA = best overall value and simplest implementation

ISO = good performance, but at a higher cost

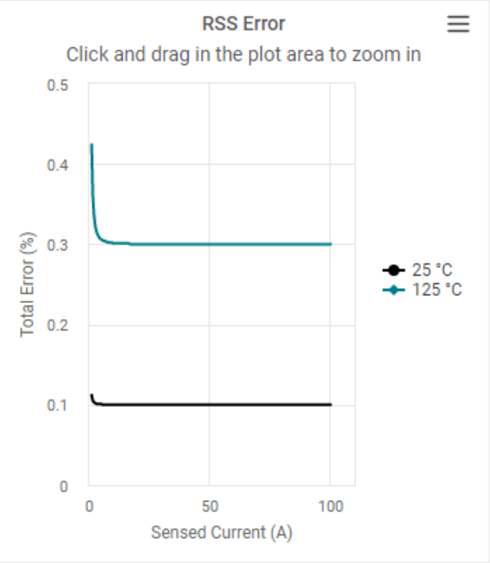
MCS = good value, but sensitive to magnetic/mechanical design

Error tool on ti.com

Current sense amplifier error analysis INA229-Q1

	Min	Max		Range
Ideal shunt resistor		2	mΩ	0.001 to 100 mΩ
Sensed current range	1	– 100	A	0.0001 to 100 A
Supply voltage		5	V	2.7 to 5.5 V
Common-mode voltage		48	V	-0.3 to 85 V
Operating temperature		125	°C	-40 to 125 °C

Update



X scale:

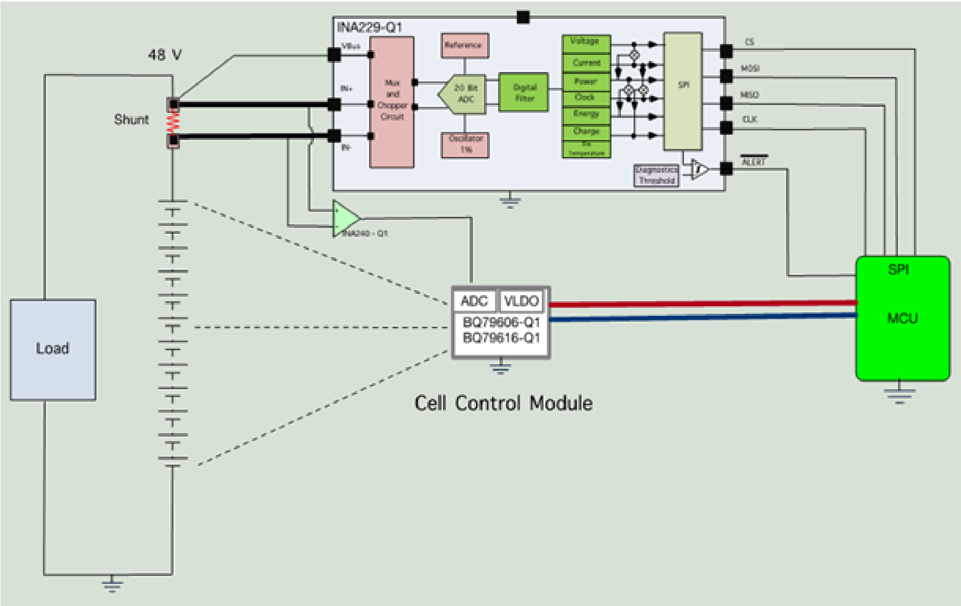
- Linear (selected)
- Logarithmic

Export to Excel

Note: The error tool uses ***RSS*** (root-sum-of-squares) error of ***worst-case specs***

AUTOMOTIVE 48-V APPLICATIONS

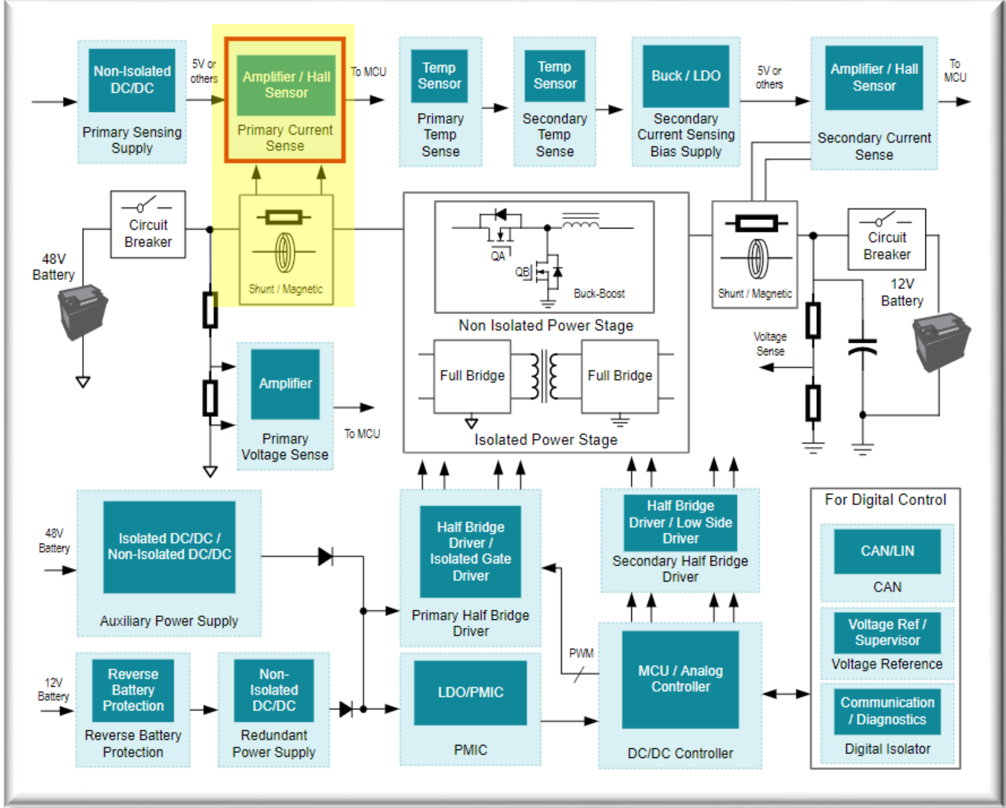
48-V battery management (BMS)



V_{CM}	48V	Error at 1600A Current:	0.10%
V_{SUPPLY}	5V	Error at 100A Current:	0.10%
Full Scale Input	±160mV	Error at 10A Current:	0.22%
Max Current	±1600A	Error at 1A Current:	2.0%
Ideal Shunt Resistor	100μΩ	Error at 0.1A Current:	20%

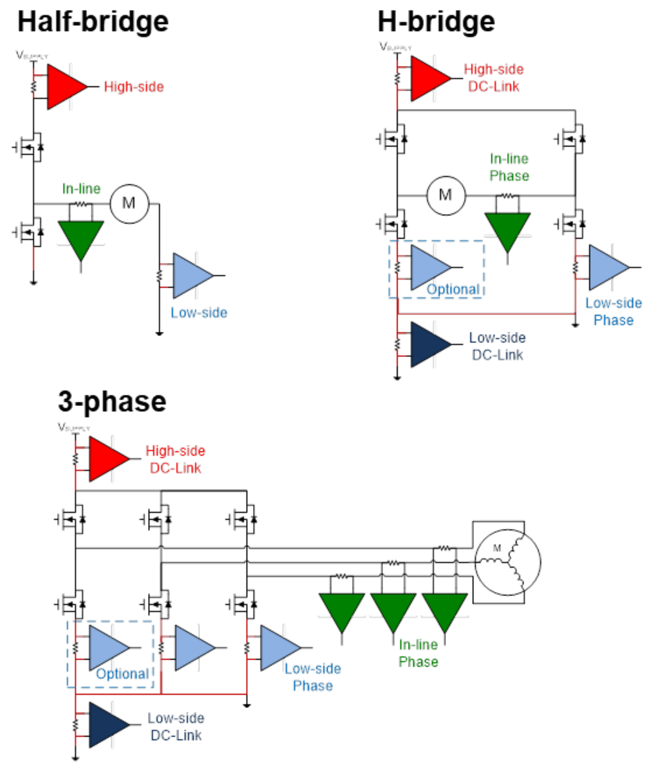
- BMS presents unique challenge of measuring bi-directional current for up to 5+ decades of dynamic range: ***±100's of mA to ±1000's of amps***
  - 1000s of amps requires sub–100μΩ shunt resistor
  - Low value shunt drives extremely low offset requirement to measure small currents.
- **INA229-Q1**
  - 1μV offset to allow use of low value shunts needed for high current
  - ENOB=20 with 160mV full scale input extends dynamic range achievable
  - Alert diagnostics can be used to detect Over Currents using GPIO
- INA240-Q1 could be used as a parallel path across shunt to improve system diagnostics and to reduce failure analysis of the shunt

48V-12V bi-directional DC/DC



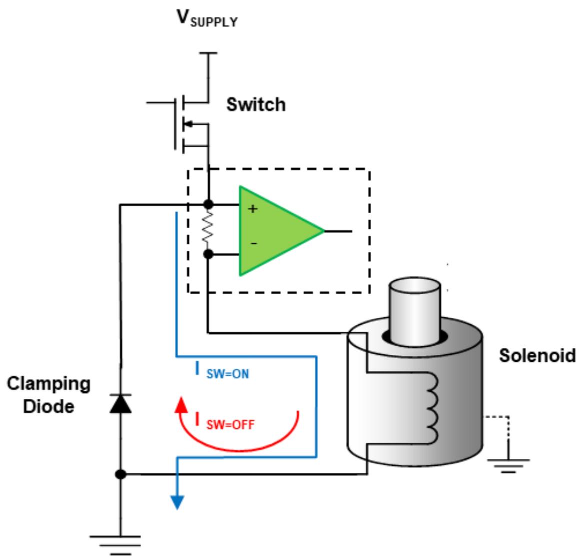
- The 48V supplies large loads such as traction motor, air-conditioning, and starters.
- Common mode range must survive up to 90V minimum and preferred to survive up to >100V
- INA240-Q1 or INA293-Q1 offer enhanced performance with industry leading:
  - Survivable common mode voltage up to 120V
  - Offset voltages less than 50µV enable the use of lower ohmage shunt resistors enabling more power efficient designs
  - Gain error of less than 0.2% with zero-drift to enable stable measurements regardless of operating environment

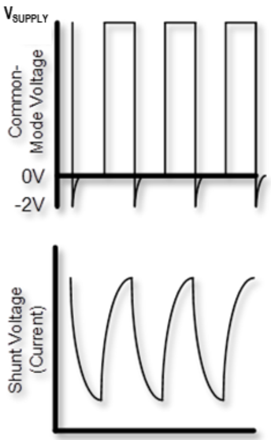
48V DC motor drive



- High-side DC-Link: INA290-Q1, INA293-Q1
  - Stable V_{CM}
  - Enables ability to detect load shorts to ground
  - Uni-directional current
  - High common-mode voltage amplifier
  - Driver current is not equal to phase current
- In-line phase: INA240-Q1
  - True phase current at all times, NO guess work
  - Best for maximizing motor control efficiency
  - PWM common-mode voltage seen by amplifier
  - High common-mode voltage combined with high dV/dT poses steep challenge to amplifier
  - Signal's frequency contents
    - The differential signal (useful information) is relatively narrow-band, and small;
    - The common mode PWM signal (not useful) is wide-band and BIG.
  - ***An ideal inline sensor amplifies only differential signal and is "blind" to common mode signal → INA240–Q1!***

48V solenoid





- High side drive, high side sense
- High side drive disconnects solenoid from high voltage power to extend solenoid lifetime
- High side sense avoids ground bouncing and allows for short to GND fault detect.
- *Challenges: a fast switching PWM common mode voltage between 48V and negative voltage*
- ***INA293-Q1, INA240-Q1, and INA253-Q1 address both challenges well with high bandwidth and wide CMV range***

KEY 48V AUTOMOTIVE PRODUCTS

AEC-Q100 Portfolio ≥48V

Existing | New Release | Q100 Option Available | Q100 in Development

High Precision:
- *VOS ≤ 100µV*
- *Gain Err ≤ 0.5%*

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

INA293
-4V to 110V CMR
-20V to 120V Survivability
20µV Offset , 0.15% Gain Error
1.3MHz BW & 2.5V/µs slew rate
Gains: 20, 50, 100, 200, 500V/V
SOT-23 Dual Pinouts

INA290
2.7V to 110V CMR
-20V to 120V Survivability
25µV Offset , 0.25% Gain Error
800KHz BW & 3V/µs slew rate
Gains: 20, 50, 100, 200, 500V/V
SC-70

Mid-Performance:
- *VOS ≤ 1mV*
- *Gain Err ≤ 1.5%*

LMP8601 Family
-22V to +60V CMR
1mV Offset , 0.5% Gain Error
Gains: 20, 50, 100V/V
Split Stage for Filtering
AEC-Q100 Grade 0 (Gain=20)
SOIC-8

LMP8480 – 8481
4.5V to +76V CMR
265uV Offset , 0.8% Gain Error
Gains: 20, 50, 60, 100V/V
MSOP-8

INA282 Family
-14V to +80V CMR
70uV Offset , 1.4% Gain Error
Gains: 50, 100, 200, 500, 1000
CMRR: 140dB Minimum
SOIC-8 & MSOP=8

High Bandwidth

INA193 Family
-16V to +80V CMR
2mV Offset , 2.5% Gain Error
Gain Options: 20, 50, 100V/V
SOT-23 Dual Pinouts

INA270 – 271
-16V to +80V CMR
2.5mV Offset , 2.5% Gain Error
Gain Options: 14, 20V/V
Split Stage for Filtering
SOIC

INA281
-4V to 110V CMR
-20V to 120V Survivability
500µV 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 110V CMR
-20V to 120V Survivability
500µV Offset , 0.5% Gain Error
800kHz BW & 3V/µs slew rate
Gains: 20, 50, 100, 200, 500V/V
SC-70

Digital Output Current/Voltage/ Power Monitors

INA228/INA229
0V to +85V CMR
1uV Offset & 0.1% Gain Error
20-bit ADC
SPI (229) and I2C (228) Outputs
VSSOP-10

INA238/INA239
0V to +85V CMR
10uV Offset & 0.25% Gain Error
16-bit ADC
SPI (239) and I2C (238) Outputs
VSSOP-10

INA240

-4 to 80V, Bi-directional, Ultra-Precise Current Sense Amplifier w/ Enhanced PWM Rejection

Features

- Enhanced PWM Rejection minimizes impact of high dV/dt common mode voltage transitions
- Wide Common-Mode : -4V to 80V
- High AC CMRR: 93dB @ 50kHz
- High Accuracy
  - Input Offset Voltage: ± 25µV (Max) with 0.25µV/°C Max Drift
  - Gain Error: ±0.25% (Max) with 2.5ppm/°C Max Drift
  - AC CMRR: ≥ 93dB @ 50kHz
  - DC CMRR: ≥ 120dB
  - PSRR: ≤ ±10 µV/V
- Available Gains: 20, 50, 100, 200V/V
- Bi-Directional current sensing
- Packages: TSSOP-8, SOIC-8
- Functional-safety capable AEC–Q100 Grade 1 & Grade 0 (SOIC)

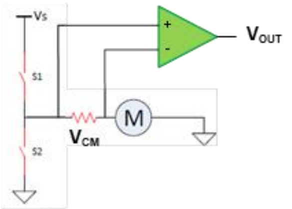
Applications

- Motor Control
- Pressure Regulator
- Solenoid/Valve Control
- Power Management

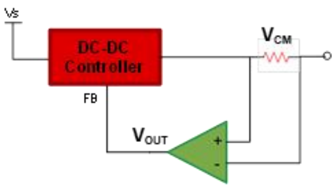
Benefits

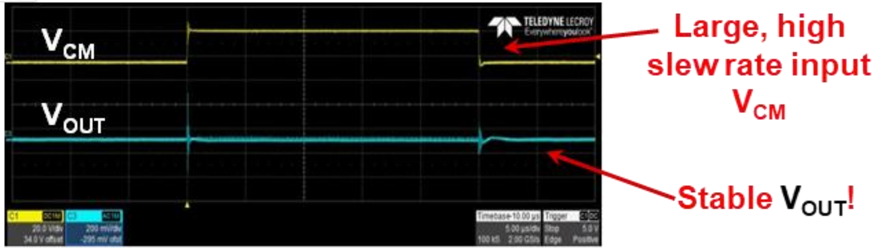
- Enhanced PWM Rejection allows for direct in-line motor current sensing
- Large input range to integrate into increasing common-mode voltage applications
- High accuracy minimizes system margins

Ex: In-line Motor Current Sensing



Ex: High-side DC-DC Current Sensing





INA290 family

110V High Voltage, High-Side, High Bandwidth, Unidirectional Current Sense Amplifier in SC-70 Package

Features

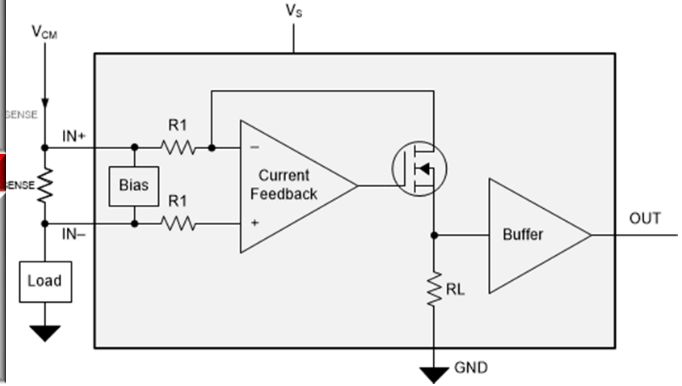
- 2.7V to 110V Common-Mode Range
  - -20V to 120V Survivability
- DC Accuracy:
  - Offset: 25µV (MAX) with 0.5µV/°C drift
  - Gain Error: 0.25% (MAX) with 10 ppm/°C drift
- High Speed: 800KHz 3dB bandwidth and 3V/µs slew rate
- Gain options: 20V/V, 50V/V, 100V/V, 200 V/V, 500V/V
- DC Supply: 2.7V to 20V
- Available in SC-70 (2mm x 1mm) Package
- AEC–Q100 Grade 1 Option Planned in 4Q20

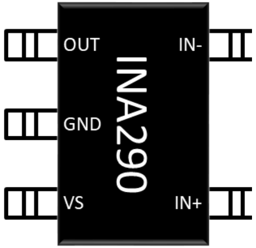
Benefits

- Wide common mode range supports 12V,24V,48V,60V,72V rails
  - Support negative transients survivability in harsh Inductive loads
- Low offset and Low gain error enables
  - improves system accuracy over temperature (-40°C to 125°C)
  - accurate lower current measurements
  - smaller shunt values (< 1mΩ)
- High Bandwidth and slew rate supports faster signal throughput
  - Ripple current measurement
  - Faster current throughput for protection
- Multiple Gain options increase design flexibility
- SC-70-5 package enables industry’s smallest amplifier with least board

Applications

- 48V Automotive BMS
- Solenoid Control
- 48V Server
- 54V Telecom
- 60V Industrial Auto Transport
- 54V PA Biasing & Monitoring





INA293 family

110V High Voltage, High Bandwidth, Unidirectional Current Sense Amplifier

Features

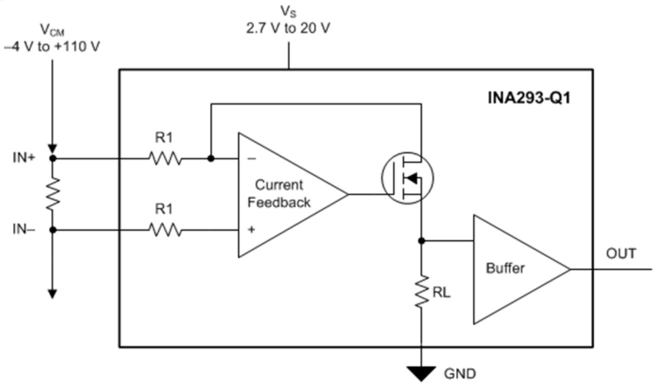
- -4V to 110V Common-Mode Range
  - -20V to 120V Survivability
- DC Accuracy:
  - Offset: 20µV (MAX) with 0.25µV/°C drift
  - Gain Error: 0.15% (MAX) with 10 ppm/°C drift
- High Speed: 1.3MHz 3dB bandwidth and 2.5V/µs slew rate
- Gain options: 20V/V, 50V/V, 100V/V, 200 V/V, 500V/V
- DC Supply: 2.7V to 20V
- Available in two SOT23-5 pin-out configurations
- AEC Q100 Option Planned in 3Q20

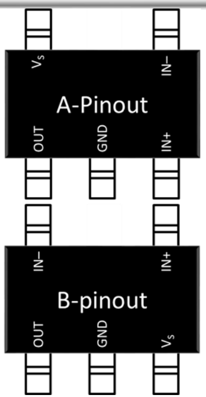
Benefits

- Wide common mode range supports 12V,24V,48V,60V,72V rails
  - -20V common mode survivability supports large inductive kick backs.
- Low offset and Low gain error enables
  - improves system accuracy over temperature (-40°C to 125°C)
  - accurate lower current measurements
  - smaller shunt values (< 1mΩ)
- High Bandwidth and slew rate supports faster signal throughput
  - Ripple current measurement
  - Faster current throughput for protection
  - Reduces blanking times in PWM applications
- Multiple Gain options increase design flexibility
- Wide supply range to support high voltage analog PID feedback systems.

Applications

- 48V Automotive
- Solenoid Control
- 48V Server
- 48V Telecom
- 60V Industrial Auto Transport
- PLC Digital Output Control





INA229

85V 20–bit, Bi-directional, SPI Power/Energy/Charge Monitor

Features

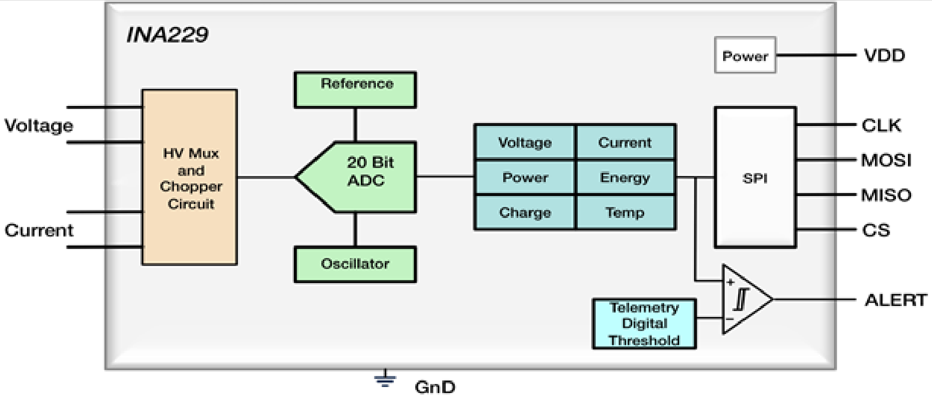
- -0.3V to 85V Common Mode Voltage
- Shunt Voltage ADC Specifications
  - Full Scale Range (+/-160mV or +/-40mV) with 20-bit Resolution (300nV/LSB or 70nV/LSB)
  - High Common Mode Rejection Ratio of 126dB (Min)
  - Offset: 1uV (Max at VCM=0V) with 0.05uV/°C (Max) Drift
  - Gain Error : 0.10% (Max) with 20ppm/°C (Max) Drift
  - Internal 1% Oscillator for Precision Energy/Charge Measurement
- Telemetry
  - Voltage, Current: <0.2% Error
  - Power, Time, Energy, Charge: <1% Error
  - Internal Temperature: ±3°C
- AC Specifications
  - Programmable conversion time/ Sampling Average
    - 50uS – 14bits
    - 1mS to 64mS– 20 bits
  - Fastest Over Current Alert threshold: 50uS
- DC Supply: 2.7V – 5.5V with Iq Operation < 1mA
- AEC–Q100 Option

Benefits

- Wide common mode range supports low-side, 24V,48V,60V Power Rail systems.
- 20Bit ADC resolution,
  - 120dB of dynamic range measurements
  - Low offset and Gain error enables low ohmic shunts, (μΩ)
  - Low temperature drift eliminates over temperature calibration
- Accurate Power/Energy and Charge estimation
- Programmable Conversion time to maximize system noise measurement
- Multi alert system that can detect
  - Over current, Under current
  - Under Voltage, Over Voltage
- SPI output mode to support high speed data throughput

Applications

- 48V Automotive BMS
- 48V Servers
- AISG Modem Control
- Renewable Energy Monitoring
- PA Bias Control
- 48V PoE systems



TMCS1100

Precision, Bi-directional, Galvanically Isolated Current Sensor with External Reference

Features

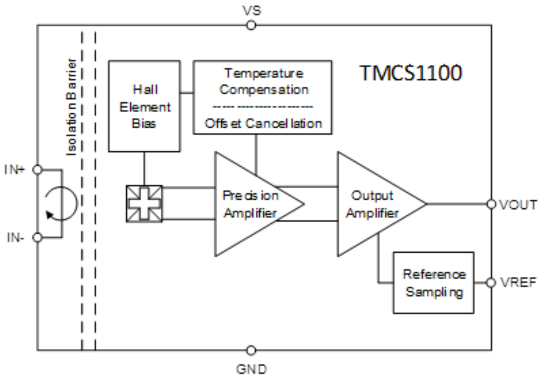
- 80 kHz signal bandwidth
- 1% Accuracy (-40 to 125°C)
- ±600 V Working Voltage, 3 kV Dielectric Isolation (IEC 60950-1)
- Operating voltage: 3.0 V to 5.5 V
- 20 A max continuous DC/RMS current (thermally limited)
- Multiple sensitivities for wide linear measurement ranges
  - TMCS1100A1: 50 mV/A
  -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

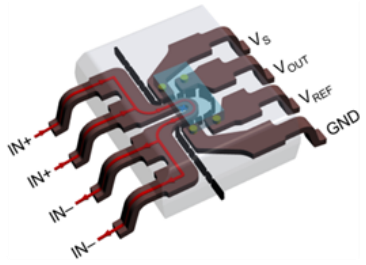
Benefits

- 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





QUIZ TIME!

Quiz

- Which of the following is not an advantage of using isolated amplifiers (such as AMC1301) for current sensing?
  - Supports up to kV of common-mode range
  - Wide variety of gain options
  - High measurement accuracy
  - Still provides isolated sensing at low voltages

- Which of the following is an advantage of using current sense amplifiers (such as INA293) for current sensing?
  - High performance vs. cost
  - Simple to implement in a system
  - Floating input stage allows VCM > VS
  - All of the above

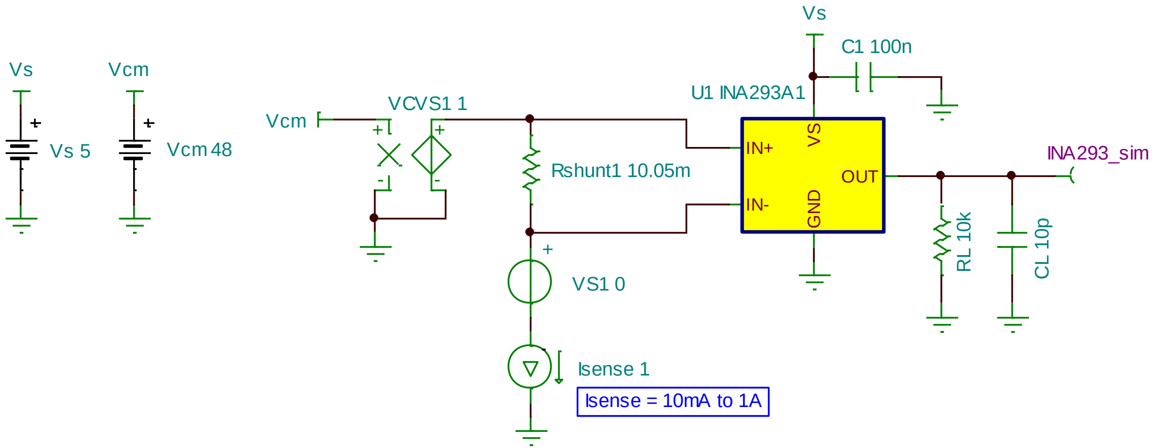
Quiz, cont.

- A device SPICE model is usually designed to ____________ datasheet specs.
  - Min/max
  - Worst-case
  - RSS of worst-case
  - Typical

- The ti.com CSA error tool plots ____________ error.
  - Min/max
  - Worst-case
  - RSS of worst-case
  - Typical

Quiz, cont.

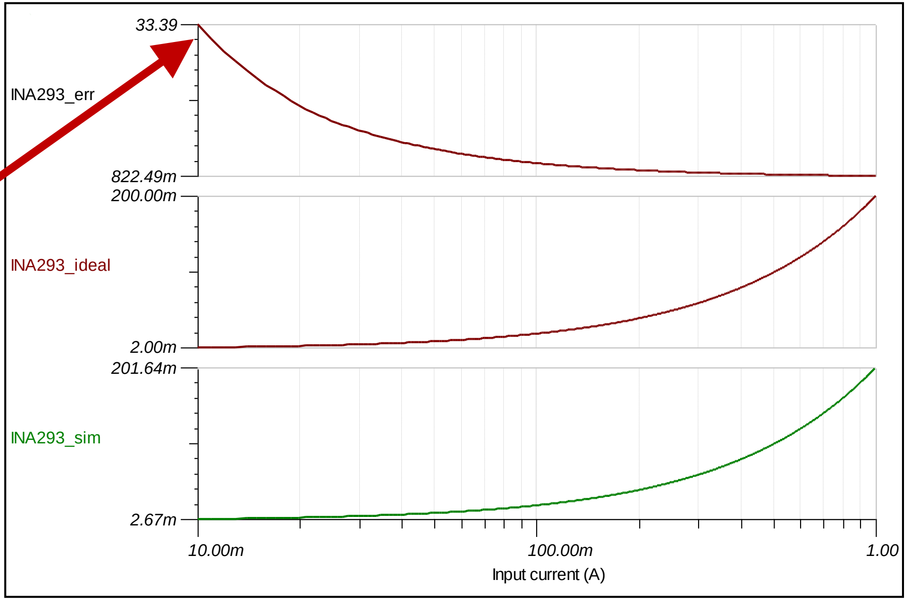
- For the circuit simulating INA293-Q1 shown?
  - What is the current that will produce the worst DC error?
  - What is the dominant error source in this worst case?
  - How can the error be reduced without changing amplifiers?
  - What is the max power dissipation if R_{SHUNT}= 100mΩ?



Quiz, cont.

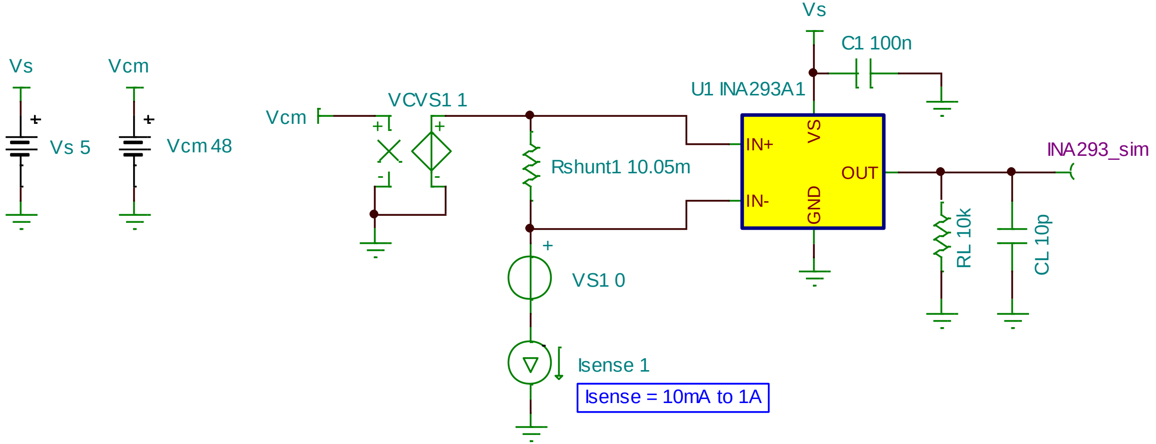
- For the circuit simulating INA293-Q1 shown?
  - What is the current that will produce the worst DC error?
    - 1A
    - 500mA
    - 10mA

Worst error occurs at minimum current, ~33.4%



Quiz, cont.

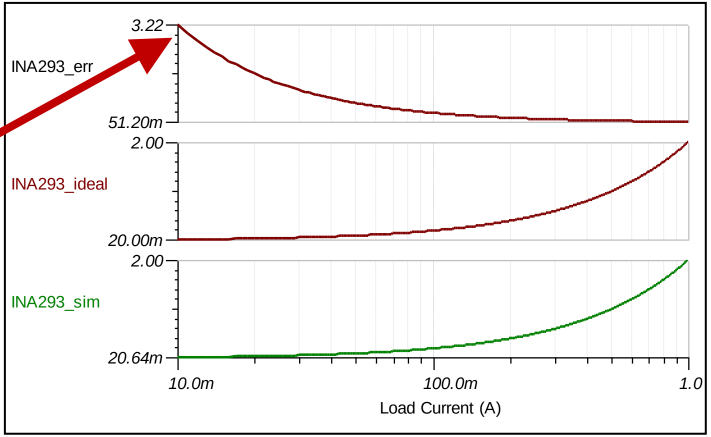
- For the circuit simulating INA293-Q1 shown?
  - What is the dominant error source in this worst case?
    - INA293-Q1 gain error
    - Shunt tolerance
    - INA293-Q1 V_{OFFSET}
    - INA293-Q1 CMRR



Quiz, cont.

- For the circuit simulating INA293-Q1 shown?
  - How can the error be reduced without changing amplifiers?
    - Add a filter to input
    - Increase shunt resistor value
    - Change output filter values

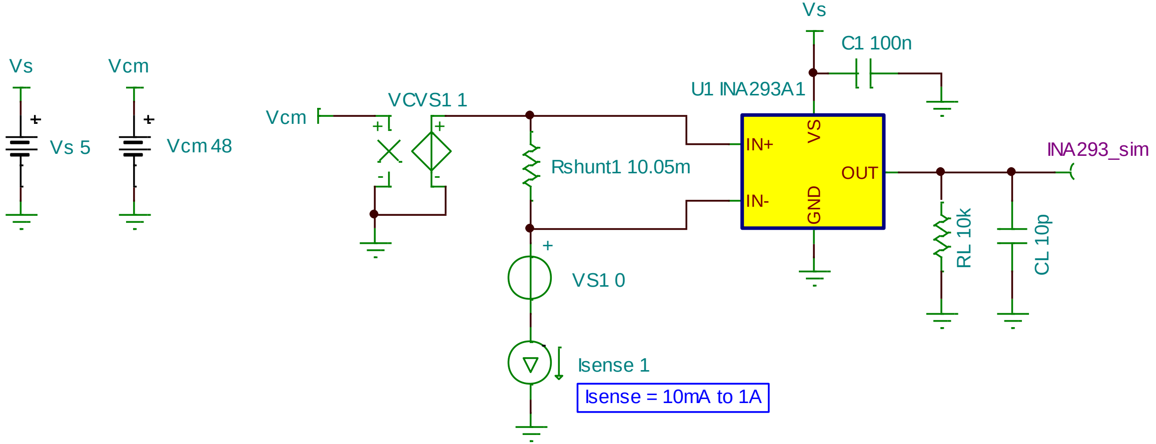
At 100mΩ, error drops to 3.2%



Quiz, cont.

- For the circuit simulating INA293-Q1 shown?
  - What is the max power dissipation if Rshunt = 100mΩ?
    - 1W
    - 500mW
    - 100mW
    - 10mW

$$P_{DIS} = I^2 * R = (1A)^2 * 100m\Omega = 100mW$$



THANK YOU!