

Simplifying Current Sensing

How to design with current sense amplifiers

Table of contents

Introduction	3
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Chapter 1: Current-sensing overview

How integrated-resistor current sensors simplify PCB designs.	4
Shunt-based current-sensing solutions for BMS applications in HEVs and EVs	6
Common uses for multichannel current monitoring	9
Power and energy monitoring with digital current sensors	11
12-V Battery Monitoring in an Automotive Module ...	14
Simplifying voltage and current measurements in battery test equipment.....	17

Chapter 2: Out-of-range current measurements

Measuring current to detect out-of-range conditions .	20
Monitoring current for multiple out-of-range conditions	22
High-side motor current monitoring for overcurrent protection	25

Chapter 3: Current sensing in switching systems

Low-drift, precision, in-line motor current measurements with enhanced PWM rejection.	28
High-side drive, high-side solenoid monitor with PWM rejection	30
Current-mode control in switching power supplies ...	32
Switching power-supply current measurements	34
Increasing measurement bandwidth for low-side shunt current monitoring using high-speed amplifiers.	37

Chapter 4: Integrating the current-sensing signal chain

Integrating the current-sensing signal path	40
Integrating the current-sense resistor	42
Integrated, current-sensing analog-to-digital converter.....	45
Enabling Precision Current Sensing Designs with Non-Ratiometric Magnetic Current Sensors	48

Chapter 5: Wide VIN and isolated current measurement

Interfacing a differential-output (isolated) amplifier to a single-ended-input ADC	50
Extending beyond the maximum common-mode range of discrete current-sense amplifiers.	52
Low-Drift, Precision, In-Line Isolated Magnetic Motor Current Measurements	55

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Introduction

Designers are faced with many options to solve the challenges associated with designing an accurate current-measurement circuit for cost-optimized applications. Approaches range from using general-purpose operational amplifiers (op amps) or analog-to-digital converters (ADCs), whether they be standalone or embedded in a microcontroller (MCU), and provide the ultimate flexibility to leveraging a wide range of tailored components specifically designed for current sensing but also address challenges in a specific way.

An additional challenge is how to quickly and efficiently narrow down the list of potential devices that align best with your particular system's requirements. TI application notes solve this challenge not only by addressing specific use cases, but also by focusing on identifying a circuit/function problem statement and

providing an outline of any challenges associated with that function. Additionally, TI application notes outline a short list of potential devices capable of supporting that particular function, as well as some alternative solutions that may be beneficial for other circuit optimizations.

This e-book's collection of application notes is not an exhaustive list of all current-sensing challenges and TI application notes, but it does address many of the more common and challenging functional circuits seen today. If you have any questions about the topics covered here or any other current-sensing questions, submit them to the Amplifier forum on TI's E2E™ Community.

Chapter 1: Current-sensing overview

How integrated-resistor current sensors simplify PCB designs

The most common way to measure current is to sense the voltage drop across a shunt or current-sense resistor. To achieve a highly accurate measurement of the current, you'll need to examine the parametric values of both the resistor and current-sense amplifier. Proper layout of the connections between the current-sense resistor and current-sense amplifier are critical to avoid a reduction in accuracy.

Figure 1 shows a typical schematic of a current-sense amplifier, with connections for both high-side current sensing and the critical design areas shaded.

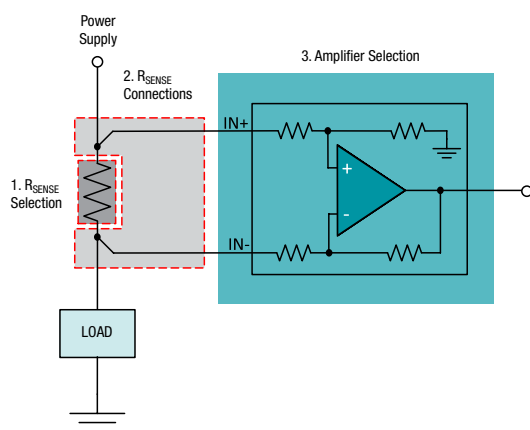


Figure 1: High-side current sensing with shaded error sources

One of the most important design decisions to make when using a current-sense amplifier is the selection of the current-sense or shunt resistor. The first design decision is usually the selection of resistor value and wattage. The value of the resistor is usually based on achieving a desired maximum differential voltage at the highest expected current. The resistor value may also be based on the power-loss budget.

Once you've determined the value and wattage of the current-sense resistor, the second parameter to consider is the resistor tolerance, since it will directly

impact the accuracy of the sensed voltage and current measurement. However, designers often overlook a more subtle parameter – the resistor temperature coefficient. The temperature coefficient is often specified in parts per million per degree Celsius, and it's important, since the temperature of the resistor will rise due to the power dissipated as current flows through the component. Lower-cost resistors will often specify a tolerance less than 1%, but will suffer in the real application due to the resistor temperature drift.

Once you've selected the resistor, you'll need to pay attention to its printed circuit board (PCB) layout in order to achieve accurate measurement results. To achieve accurate current measurements, there must be four connections to the current-sense resistor. Two connections should handle the current flow while the other two sense the voltage drop across the resistor.

Figure 2 shows various ways to monitor the current flow through a resistor.

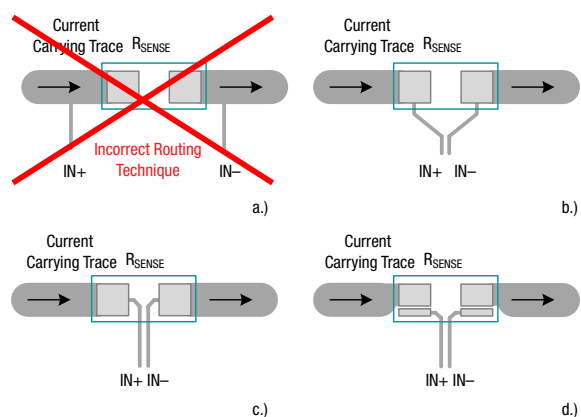


Figure 2: Current-sense resistor layout techniques

One of the most common mistakes in laying out the current-sense resistor is connecting the current-sense amplifier inputs to the current-carrying trace instead of directly to the current-sense resistor, as shown in **Figure 2a**. **Figure 2b**, **2c** and **2d** show other valid methods to lay out the connections to the current-sense resistor.

The layout in **Figure 2d** features independent four-wire (Kelvin) connections to the current-sense resistor. This technique is most commonly used when the value of the shunt resistor is below $0.5\text{ m}\Omega$ and the solder resistance in series with resistor connections appreciably adds to the overall shunt resistance. It is difficult to know which layout technique will yield the best results on the final PCB design, since the resistance accuracy depends greatly on the measurement location used when the resistor was manufactured. If the resistor value was measured on the inside of the pads, then the layout shown in **Figure 2c** will provide the best measurement result. If the resistor value was measured at the side, then the layout shown in **Figure 2b** will provide the highest accuracy. The difficulty with selecting the best layout is that many resistor data sheets do not provide a layout recommendation for the best current-sensing accuracy, nor do they mention the measurement point used in the manufacturing process.

Using a current-sense amplifier with an integrated current-sense resistor simplifies the difficulties around resistor selection and PCB layout. TI's [INA250](#), [INA253](#) and [INA260](#) devices feature a current-sense resistor integrated inside the same package as the current-sense amplifier. Connections to the current-sense resistor are optimized to achieve the best measurement accuracy and temperature stability. The [INA250](#) and [INA253](#) are analog output current-sense amplifier, while the [INA260](#) is a digital output current sensor that reports the current, power and bus voltage through an I2C/ System Management Bus (SMBus) interface. **Figure 3** is a block diagram of the [INA250](#), along with the resistor connections.

These devices provide external sense connections that enable the filtering of the shunt voltage or direct connections to the current-sense amplifier. Connections to the shunt resistor are fixed internally, therefore reducing PCB layout difficulty. The gain of the amplifier is optimized for each resistor so that the total system gain error is comparable to using a 0.1% or better current-sense resistor. The integrated shunt technology used in

the [INA250](#), [INA253](#) and [INA260](#) can support operating currents as high as 15 A .

The incorporation of the resistor into [INA250](#), [INA253](#) and [INA260](#) accuracy specifications simplifies component selection. The [INA250](#) has a maximum total system gain error of 0.3% at room temperature and 0.75%

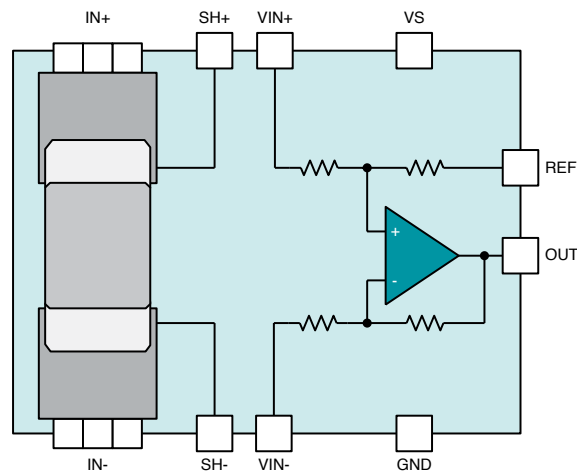


Figure 3: [INA250](#) block diagram with internal resistor connections

over the -40°C to 125°C temperature range. Accuracy calculations with devices that do not have the integrated shunt resistor have to factor in the device gain error, gain error drift, resistor tolerance and resistor drift to get the overall system gain error; therefore, it can be difficult to pick components to meet an overall system accuracy specification. The [INA253](#) is an 80 V capable device also with a gain error of 0.75% over the -40°C to 125°C temperature range. The [INA260](#) is a digital current output device that features a maximum total room-temperature gain error of 0.15% . This total gain error already includes the variation of the integrated resistor and the gain error of the current-sense amplifier. The connections to the current-sense resistor are internal to the package and calibrated for each device in order to remove variations from the resistor connection points.

In designs that require precise current measurements, integrated shunt products can provide higher accuracy and enable a lower total solution cost. Achieving similar accuracy to the [INA260](#) would require a current-sense

amplifier with a gain error less than 0.1% and a low-drift resistor with an initial tolerance less than 0.05%. In general, high-wattage resistors with accuracy less than 0.1% are costly and can be as high as several dollars in 1,000-unit volumes.

Another advantage of the integrated resistor in the INA260 is that the resistor value is already calibrated and set internally, so returned values for current are easily converted to amperes. Other digital solutions require programming the value of the current-sense resistor either internally or in the host processor so that the returned current readings scale appropriately.

The integrated shunt technology used in the INA250,

INA253 and INA260 allows for precision current measurements, reduced layout complexity and better understanding of the total system error, and can be lower cost than solutions with equivalent accuracy. In applications that require precision but need to support currents higher than 15 A, you can parallel multiple either the INA250 or INA253 devices in a daisy-chain configuration (as shown in its data sheet), or use multiple INA260 devices, as long as the host processor can sum the reported current readings. If paralleling multiple devices to monitor currents higher than 15 A is not practical due to the solution size, **Table 1** provides a list of devices that you can use to monitor higher currents using external shunt resistors.

Device	Optimized parameters	Performance trade-off
INA226	Digital output with I2C interface, 0.1% gain error, 10µV offset	Shunt resistor is external
INA233	Digital output with PMBus/I2C interface, 0.1% gain error, 10µV offset	Shunt resistor is external
INA210C	Analog output, 0.5% gain error, 35µV offset	Shunt resistor is external

Table 1: Alternative device recommendations

Device	Application Note
SBOA170B	“Integrating the Current Sensing Resistor”
SBOA167A	“Integrating the Current Sensing Signal Path”
SBOA169A	“Precision, Low-Side Current Measurement”

Table 2: Related TI application notes

Shunt-based current-sensing solutions for BMS applications in HEVs and EVs

Hybrid electric vehicles (HEV) and electric vehicles (EV) continue to gain share in the overall global automotive market. The battery management system (BMS) for these vehicles carries out the important tasks of keeping the battery operating inside the safe operating area (SOA), monitoring power distribution, and keeping track of the state of charge (SoC).

In a typical HEV and EV, both high- and low-voltage subsystems are present. The high-voltage subsystem operates at several hundred volts, and interfaces directly with utility grid or high-voltage dc sources. The low-voltage subsystem generally operates at 48 V and 12 V.

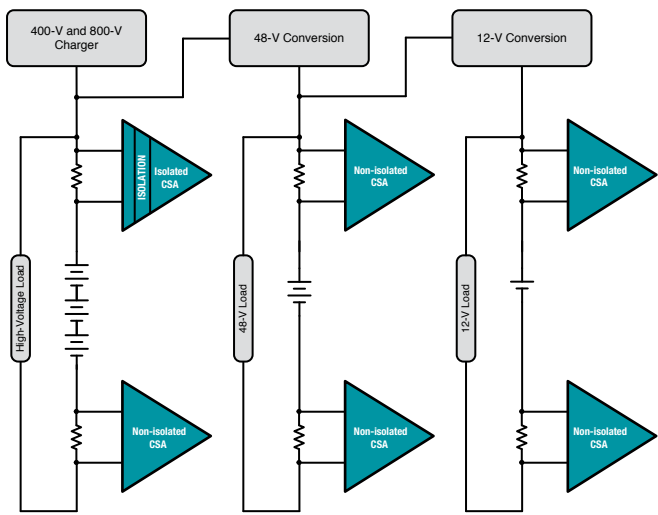


Figure 1. Topologies of Current Sensing in BMS

TI offers a variety of isolated current sensing devices that can be used in high-voltage BMS systems. Among them is the [DRV425](#), which is fluxgate technology based. The [TIPD205](#), ± 100 -A bus bar current sensor using open-loop fluxgate sensors reference design illustrates how this design is achieved. A summary of other examples of isolated current sensing technology can be found in the [Comparing shunt- and hall-based isolated current-sensing solutions in HEV/EV application note](#). Here, however, the focus is solely on a nonisolated, high-side, shunt-based current-sensing amplifier (CSA), also called a current shunt monitor (CSM), in 12-V to 48-V BMS subsystems.

Low Voltage (12-V to 48-V) BMS Current Sensing

The advantages of nonisolated shunt-based current sensing include simplicity, low cost, excellent linearity, and accuracy. On the other hand, limited common-mode range can restrict application in a high-side current-sensing configuration.

Another drawback of shunt-based current sensing is that at high-current levels, power dissipation by the shunt can potentially be significant.

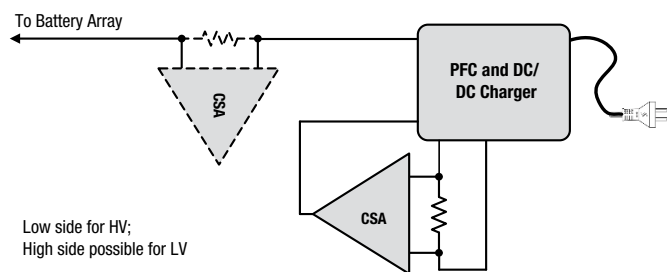


Figure 2. Current-Sensing Amplifiers in an HEV or EV Charger

Battery array is an important component of any HEV or EV. There are mainly two types of rechargeable batteries: The lead acid battery that has been around for over 100 years, and the Li-Ion battery that has only been put into practical use since the 1980s. At the time of this publication, there is a continued, tremendous research effort to introduce new types of batteries, such as aluminum air and zinc air batteries. The ultimate goal is to commercialize the next game changer; a battery that is safer, longer lasting, and lower maintenance

with higher power density. When it comes to battery management, there are many differences between lead acid and Li-Ion batteries. However, there are also many similarities. Both types follow a certain constant voltage-constant current (CV-CC) charging profile. The CSA plays an important role in making sure the battery remains within the SOA. Charging current can be quite high, and can reach hundreds of amps. Historically, measuring this current with shunt-based topologies has been challenging. However, with the availability of ultra-low resistance shunts, the option is now viable.

On the other hand, a BMS system must monitor the power distribution as accurately as possible during normal operation in order to provide overall system health and safety information. State of charge (SoC), which is the equivalent of a fuel gauge for the battery pack in an HEV or EV, correlates to driving range. Current sensing and integration is one of the important methods to determine SoC. Even when the engine is shut off, not all onboard electronics are completely turned off. These off-state currents contribute to the overall leakage current, and there is a strong desire to have the leakage current monitored and accounted for.

Ideally, a single current-sense amplifier must monitor the entire current range, from several hundred amps down to a few amps, possibly even to milliamperes. Maintaining accuracy within such a wide dynamic range is often one of the greatest challenges in designing for BMS current sensing.

Sizing the Shunt Resistor

The maximum current and power rating of the shunt resistor often determines the highest shunt value that can be used. The higher the shunt resistance, the bigger the shunt voltage, and the smaller the relative error due to system nonidealities, such as amplifier offset, gain error, and drift. However, the higher the shunt voltage, the higher the power dissipation. Excessive power dissipation causes temperature rise, which not only degrades system performance, but also can potentially be destructive when not properly controlled. On the other hand, the lowest shunt value is determined by the minimum

current and accuracy of the current-sense amplifier.

As an example, suppose the CSA offset is 10 μV , while all other error sources are negligible, and the shunt resistance is 100 $\mu\Omega$. Without calibration, for a 100-mA current, the reported current could be anywhere between 0 mA and 200 mA. If the shunt is changed to 1 m Ω , the same current is reported anywhere between 90 mA and 110 mA. In practice, a shunt resistor is often chosen to be between the two extreme values.

Choose the Correct Current Sense Amplifier

TI's precision, nonisolated current sense amplifiers offer a wide choice in terms of key parameters, such as common-mode voltage, bandwidth, offset, drift, and power consumption. Sensing current accurately over a wide dynamic range is a great challenge. The problem is especially acute at the lower end, where system error can easily overwhelm the useful signal. A system calibration becomes necessary in order to be able to subtract system error from the measurements.

Zero-drift current-sense amplifiers enable single-point calibration, and make such challenging designs possible by offering stable performance over temperature.

The [INA240-Q1](#) is an excellent choice for 48-V systems because of its 80-V common-mode specification. The [INA226-Q1](#) is a digital-output current-sense amplifier designed for up to a 36-V common-mode voltage.

The device integrates a high-performance ADC within the same chip, offering an exceptional 10- μV max offset specification. Both devices are manufactured with TI proprietary Zero-Drift technology, which makes single temperature calibration possible.

Table 1. Comparison Between INA240A1 and INA226

Key Specifications	INA240A1	INA226
Output	Analog Out	12C
Maximum VCM	80 V	36 V
Minimum VCM	–4 V	0 V
Supply voltage (VS)	2.7 V to 5.5 V	2.7 V to 5.5 V
Shunt voltage (VS = 5 V)	± 125 mV	± 81.975 mV
VOS at 12 V	± 25 xV, max	± 10 xV, max
VOS drift	0.25 xV/°C	0.1 xV/°C
Gain error	0.20%	0.10%
Noise density	40 nV/xHz	NA

In addition to the [INA226-Q1](#), TI offers other digital output current, voltage, and power monitors. Some example

products and adjacent technical documents are compiled in Table 2 and Table 3.

Table 2. Alternative Device Recommendations

Device	Digital Interface	Description
INA220-Q1	I2C, SMBUS	26-V, Bidirectional, Zero-Drift, Low- or High-Side, I2C Current/Power Monitor
INA3221-Q1	I2C, SMBUS	26-V, Triple-Channel, Bidirectional, Zero-Drift, Low- or High-Side, I2C, Current and Voltage Monitor w/ Alerts

Table 3. Adjacent Tech Notes

Literature Number	Literature Title
SBA325	Current Sensing with INA226-Q1 in HEV/EV Low Voltage BMS Subsystems
SBOA295	High Voltage, High-Side Floating Current Sensing Circuit Using Current Output Current Sense Amplifier

Conclusion

For current sensing in HEV and EV low-voltage BMS subsystems, in addition to low-side, a high-side shunt-based solution is a viable option. Zero-Drift technology enables one-time calibration, which makes low-current measurement possible. Digital output devices can further simplify the design by taking advantage of the existing communication bus.

Common uses for multichannel current monitoring

As the need for system intelligence and power efficiency continues to grow, the need for better monitoring of critical system currents is increasingly paramount. Multiple operational amplifiers configured as difference amplifiers or multiple current-sense amplifiers distributed within the system may have performed such monitoring in the past. But as the number of current-monitoring channels increases, so does the amount of external components needed to realize a solution. These additional components increase design complexity and solution size, and can degrade overall current-sensing accuracy.

For example, consider a case where you need to measure two currents, as shown in **Figure 1**.

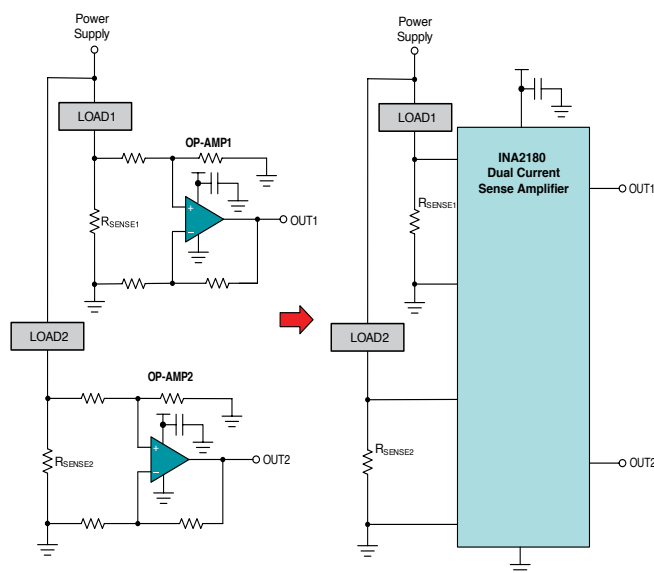


Figure 1: Discrete vs. integrated current-sensing solutions

In this case, the operational amplifier-based solution requires eight resistors to set the gain, two bypass capacitors and two current-sense resistors. The same circuit implemented with an [INA2180](#) only requires the two current-sense resistors and a single bypass capacitor. Since the integrated gain-set resistors are well matched, the accuracy of the INA2180 solution is much better than what is possible in a cost-effective discrete implementation. The integrated gain-set resistors

permit higher accuracy monitoring or enable the use of a wider-tolerance current-sense resistor for low-cost applications. The INA2180 and [INA2181](#) family are also more flexible in that they can monitor voltage drops across resistors that have voltages greater than the supply voltage.

In addition to simplifying the design process and reducing the number of external components, having multiple current-monitoring devices in a single package enables several common application solutions.

For example, consider the application shown in **Figure 2**, where an external analog-to-digital converter (ADC) monitors the total current drawn by the memory and processor.

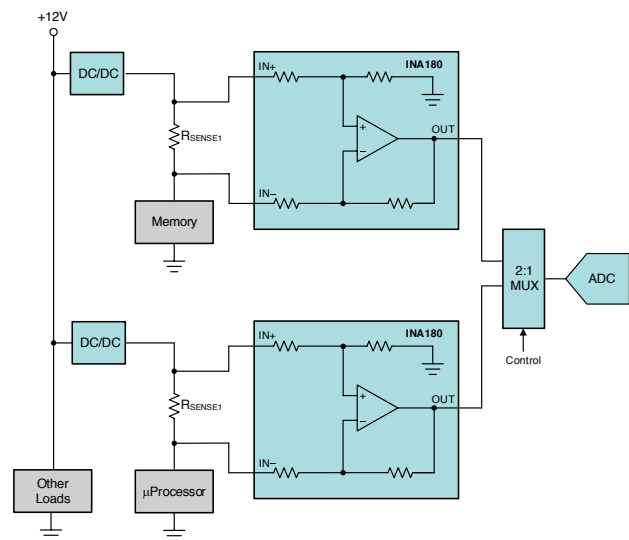


Figure 2: Monitoring total current in two supply rails

One approach would be to monitor both the central processing unit (CPU) and memory current, multiplex the current to an ADC and then add the resulting values together in a microprocessor. This approach requires some mathematical processing (as well as an ADC) to continually sample outputs at a rate fast enough to be effective. A better approach would be to use the REF pin of the INA2181 to add the current drawn by the memory to the current drawn by the CPU. You can do this by connecting the output of channel 1, which monitors the memory current, to the REF2 pin, as shown in **Figure 3**.

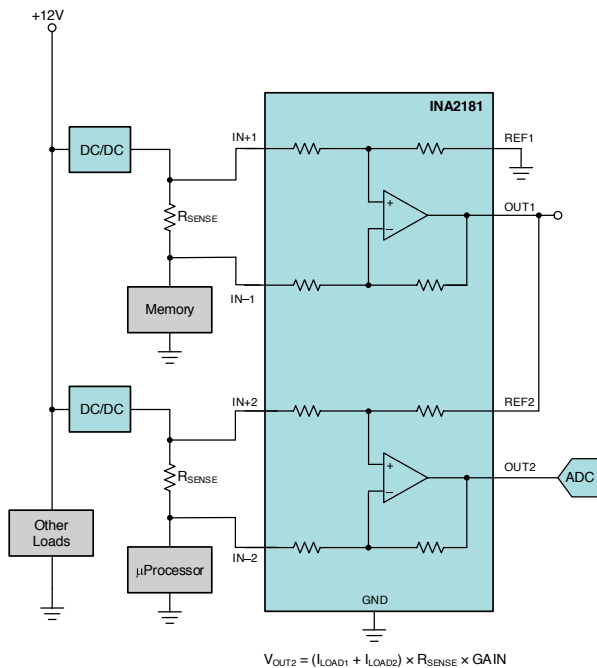


Figure 3: Analog current summing with the INA2181

Channel 2's output will be the amplified sum of the currents from the CPU and memory. An ADC can monitor the current from the memory and the current from the total. But since channel 2's output is an analog signal, a comparator with an appropriately set reference can interrupt the system when an overcurrent condition occurs. For this circuit to function properly, the values of the two sense resistors must be identical.

Another convenient use for multichannel current monitors is to detect unexpected leakage paths. These leakage paths could be caused by unintended shorts to ground or some other potential not in the current-measurement path. One technique to detect leakage-current paths is to monitor all current going into and coming out of a circuit. As long as there are no unexpected leakage paths, the current into the load must equal the current coming out.

If the currents in and out are equal, no unexpected current leakage path will be detected.

Using the dual current monitor provides a simple technique to detect leakage current paths without the need for multiple devices or having to externally add or

subtract currents. The circuit shown in **Figure 4** uses the INA2181 to monitor current into and out of a load. By reversing the polarity of the resistor connections of the second amplifier and connecting the output of the first amplifier to the second amplifier, the current going into the load is subtracted from the current going out.

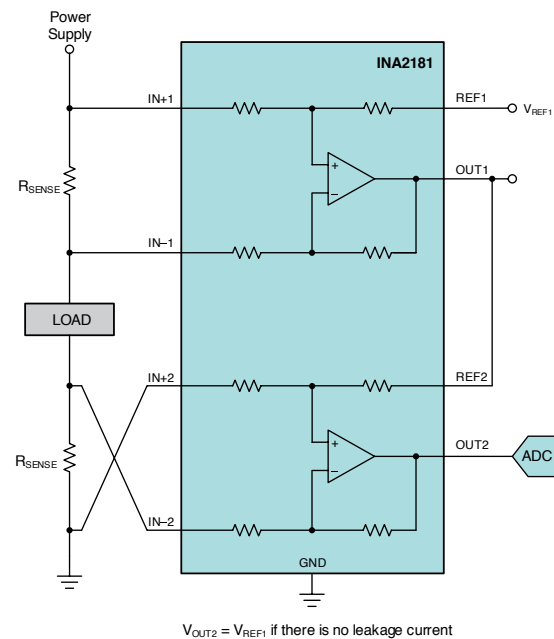


Figure 4: Current subtraction using the INA2181 for leakage current detection

If the voltage at OUT2 is equal to the applied reference voltage, then no leakage path exists. If VOUT2 is higher than the applied reference voltage, then there is unexpected current leaving the load. Similarly, if VOUT2 is below the reference voltage, then unexpected leakage current is entering the load. As before, for this circuit to function properly, the values of the current sense-resistors must be identical.

TI offers several solutions for multichannel current monitoring. To monitor four channels, the INA4180 and INA4181 devices are available with an analog voltage output. The INA3221 provides the ability to accurately measure both system current and bus voltages for up to three independent channels. The values of the currents and voltages are reported through an I2C-compatible interface.

Device	Optimized parameters	Performance trade-off
INA4180	Four-channel analog current monitor	Unidirectional measurement, larger package
INA4181	Bidirectional four-channel current monitor	Larger package
INA3221	Three-channel digital current/voltage monitor	No analog output

Table 1: Alternative device recommendations

Device	Application Note
SBOA162C	“Measuring Current to Detect Out-of-Range Conditions”
SBOA169A	“Precision, Low-Side Current Measurement”
SBOA190	“Low-Side Current Sense Circuit Integration”

Table 2: Related TI application notes

Power and energy monitoring with digital current sensors

As the demand for power-efficient systems continues to grow, accurately monitoring system power and energy consumption is increasingly important – and a problem that more engineers must solve. One solution to this problem is to use an analog-to-digital converter (ADC) for both the current and voltage and then multiply the result in a processor to obtain power. However, the communications delay and overhead between getting the current and voltage information introduces time alignment errors in the power measurement, since both the current and the voltage can vary independently of one another.

To minimize the delay between the voltage and current measurements, the processor would need to dedicate adequate processing power to ADC communications and power calculations. Even with the processor

primarily dedicated to this function, any interactions with other devices in the system could delay the voltage and current measurements and reduce power-monitoring accuracy. Adding additional responsibilities like averaging the system voltage, current and power, as well as energy monitoring, starts to further burden the processor with additional functions.

A better way to monitor power is to use a digital current monitor to handle the mathematical processing, freeing up the processor to deal with other system tasks, and only alert the processor if higher-level system actions need to occur. TI provides a wide range of digital power and current monitors to address this problem. One such device is the [INA233](#), which enables the monitoring of voltage, current, power and energy via an I2C-, System Management Bus (SMBus)-, Power Management Bus (PMBus)-compatible interface. **Figure 1** is a block diagram of the INA233.

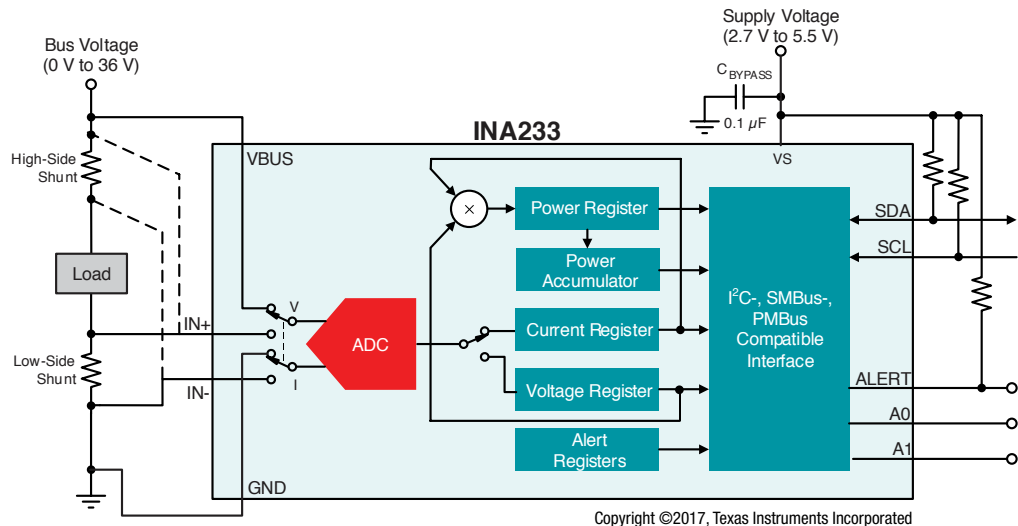


Figure 1: INA233 typical application circuit

Figure 2 is a simplified block diagram of the power-conversion engine. Power is internally calculated from the shunt and bus voltage measurements in an interleaved fashion to minimize time-alignment errors in power calculations.

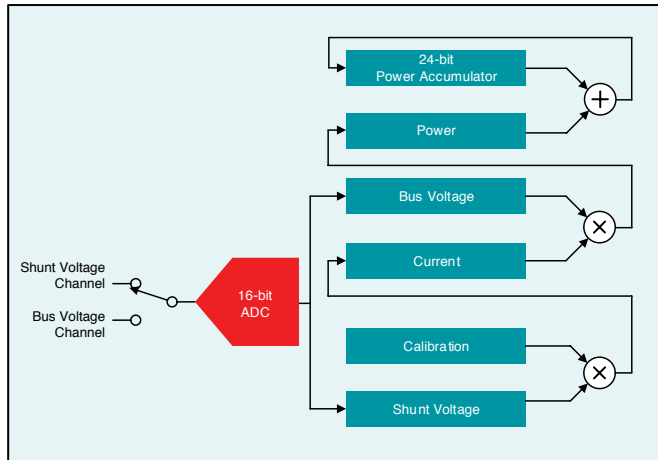


Figure 2: INA233 power-conversion engine

The internal calculations for power occur in the background, independent of ADC conversion rates or digital bus communications. The device also features an ALERT pin that will notify the host processor if the current, power or bus voltage is out of the expected range of operation. The INA233 handles fault events independently; reading internal status registers when the ALERT pin asserts enables the reporting of multiple simultaneous fault conditions. The internal processing and alert capabilities of the INA233 free the host processor to manage other tasks while the device takes care of continual system monitoring. The host processor is notified via the ALERT pin only when additional attention is required.

The INA233 also features a 24-bit power accumulator that continuously adds the current power reading to the sum of previous power readings. This power accumulator can monitor system energy consumption to get an average measurement of power consumption over time. Since power levels can fluctuate in any given instance, monitoring the energy provides a better way to gauge the average system power usage over long

intervals. Knowing the system energy consumption also provides a metric with which you can gauge system run time and power efficiency, as well as the effects of power optimizations that involve the adjustment of power-supply voltages and processor clock rates.

The ADC conversion times for both shunt and bus voltage measurements are programmable from 140 μ s to 8.244 ms. Longer conversion times are useful to decrease noise susceptibility and to achieve increased device measurement stability. **Figure 3** shows the effects of increased ADC conversion times.

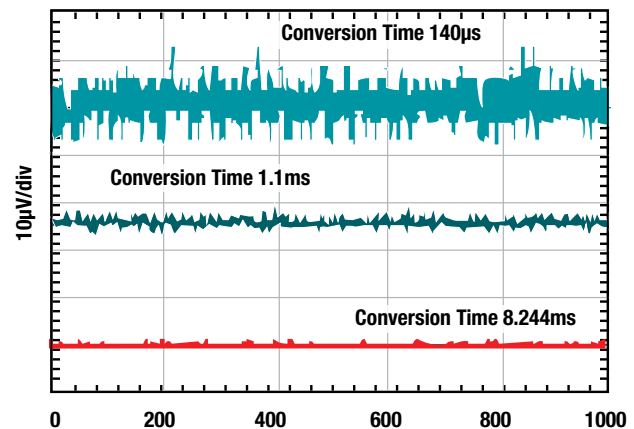


Figure 3: Noise vs. ADC conversion time

In addition to programmable ADC conversion times, the device can average up to 1,024 conversion cycles and update the internal power, current and voltage registers once the averaging is finished. Programmable conversion times along with averaging windows enable the adjustment of the device's telemetry update rate to meet system timing needs.

Even though the INA233 has built-in averaging and adjustable ADC conversion times, you must wait until the averaging is complete before reading the result. One benefit of the internal power accumulator is that it enables the host to calculate the average power on demand, eliminating the delay for the averaging interval to finish.

Taking the value of the total accumulated power and dividing by the total sample count for that accumulation period gives you an average power reading on demand, as shown in **Equation 1**:

$$\text{Average Power} = \frac{\sum_{i=1}^n \text{ADCPowerMeasurement}_i}{n}$$

$$= \frac{\text{Total Accumulated Power over } n \text{ samples}}{\text{Number of samples}}$$

Once you've calculated the average power, you can determine the energy consumption by multiplying the average power by the time interval of that average, or by multiplying the total accumulated power by the ADC conversion time, as shown in **Equation 2**:

$$\text{Energy} = \text{Average Power} \times \text{time}$$

$$= \left(\frac{\sum_{i=1}^n \text{ADCPowerMeasurement}_i}{n} \right) \times (n \times \text{ADC conversion time})$$

$$= \text{Total Accumulated Power} \times \text{ADC conversion time}$$

Since the ADC conversion time can vary by as much as 10%, it's best to multiply the average power by the time measured with an external time reference. The time interval for the energy calculation should be long enough so that the communications time due to the digital bus is insignificant compared to the total time used in the energy calculation. The size of the power accumulator in the INA233 is limited to 24 bits. The host should read the value of the accumulator periodically and clear it in order to avoid overflow. The accumulator can also be configured to clear automatically after each read.

The time to overflow will be a function of the power, ADC conversion times and averaging times. Higher power levels will cause any overflow in the power accumulator to occur faster than lower power levels. Also, longer conversion times and a higher number of averages will increase the time to overflow; in lower-power cases, the time to overflow can be extended to be several hours or even days in length.

The INA233 is one of many digital current monitors offered by TI. Table 1 shows some alternative devices that can also monitor a system and help free the host processor to handle higher-level tasks.

Device	Optimized parameters	Performance trade-off
INA226	I ² C/SMBus-compatible with reduced register set	No power accumulator, no independent fault monitoring
INA231	Wafer chip-scale package (WCSP), reduced register set, lower cost	Less accuracy, no power accumulator, no independent fault monitoring
INA219	Lowest cost, reduced register set	Less accuracy and resolution, no ALERT pin, no power accumulator
INA3221	Monitors three channels	Less accuracy and resolution, monitors bus and shunt voltages

Table 1: Alternative device recommendations

SBOA179	"Integrated, Current Sensing Analog-to-Digital Converter"
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Table 2: Related TI application notes

12-V Battery Monitoring in an Automotive Module

Monitoring current off an automotive 12-V battery provides critical data for a variety of applications such as module current consumption, load diagnostics, and load feedback control. The TI current sensing portfolio can address this space with analog and digital current sense amplifier (CSA) devices that come automotive qualified, contain integrated features, and operate in 12-V environments even though powered with low-voltage rails. This document provides recommended devices and architectures to address current sensing in this space.

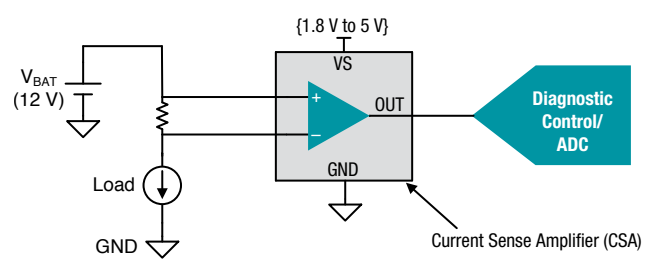


Figure 1. Current Sense Amplifier on 12-V Rail

There are constraints in this space that stem from conditions such as electrical transient protection regulations ISO7637-2 and ISO16750-2, jump-starts, reverse-polarity, and cold-cranking. In general, system-level protection and suppression schemes can be used to protect downstream circuitry from these voltage surge conditions. Types of devices included in these solutions are smart high-side switches, smart diodes, or other discrete implementations. These products may come with internal integrated current sensing features, but they often are not very accurate ($\pm 3\%$ to $\pm 20\%$ maximum error) and have limited dynamic range.

Dedicated TI current sensors are low in power consumption and highly accurate ($<1\%$ error) in automotive environments even across temperature. A matched internal gain network plus input offset zeroing provides lower measurement drift across temperature compared to either discrete solutions or ICs with supplemental integrated current sensing. This amplifier integration and technology can remove the need for temperature and system calibrations, all at low cost.

Usually, general system protection schemes do not fully suppress or protect against voltage surges, so these primary regulations translate into typical voltage survivability requirements. Depending on the system, a current sensor may need to survive load dumps, reverse battery protection, fast load-switching, and inductive kickback voltages. For example, working on a 12-V battery rail requires at least 40-V survivability during load dump conditions. It is important to choose a current sensor that has an input common-mode voltage (VCM) rating that complies with the worst-case VCM condition of the system. Otherwise, input voltage clamping schemes are needed to protect the device during such conditions.

There are multiple TI Current (Power) Sensing amplifiers that can operate on a 12-V automotive battery and survive crucial voltage levels up to 40 V and more. Ultimately, they provide very accurate, zero-drift, high bandwidth, and low-cost solutions. Using TI's Product selection tool online, Table 1 tabulates candidates for high-side current sensing on an automotive 12-V battery rail requiring 40-V survivability. It should be noted that all devices in Table 1 have multiple gain variants ranging from 20 V/V to 500 V/V.

TI Current Sense Amplifier	VCM Survivability	VOS _{MAX} (25 °C)	BW	GAIN Error _{MAX} (25°C)	IQ _{MAX} (25 °C)	Features
INA240-Q1	-6 V to +90 V	$\pm 25\ \mu\text{V}$	400 kHz	$\pm 0.2\%$	2.4 mA	PWM rejection (very high CMRR), AEC Q100 (temperature grades 1 and 0)
INA190-Q1	-0.3 V to +42 V	$\pm 10\ \mu\text{V}$	45 kHz	$\pm 0.3\%$	65 μA	More accurate version of INA186-Q1. Wide dynamic range.
INA186-Q1	-0.3 V to +42 V	$\pm 50\ \mu\text{V}$	45 kHz	$\pm 1\%$	65 μA	Low input bias current ($I_B = \pm 500\ \text{pA}$ typical). Wide dynamic range. Operates with supply voltage (VS) of 1.7 V.
INA180-Q1 (INA181-Q1)	-0.3 V to +28 V	$\pm 500\ \mu\text{V}$	350 kHz	$\pm 1\%$	0.5 mA	Single, dual, and quad channel. Uni- or bi-directional versions

Table 1. Current Sense Amplifiers for Monitoring 12-V Automotive Battery

According to Table 1, the INA240-Q1 provides the best performance, but is not optimized to monitor a 12-V battery compared to INA186-Q1, which requires less power, cost, and package size. The INA186-Q1 does have high AC CMRR (140 dB) and large dynamic range (VOUT swings to VS - 40 mV over temperature). Additionally, the INA186-Q1 possesses a unique capacitively-coupled input architecture that increases differential input-resistance by 3 orders of magnitude compared to majority of CSAs. High input-impedance allows the user to filter current noise at the device input with minimal effect on gain. Using the [datasheet](#) equation if $R_1 = 1\text{ k}\Omega$, the effective gain is reduced 43.5 m% for all variants except A1 (25 V/V). Figure 2 shows use of INA186-Q1 in battery monitoring. Filtering at the input (instead of output) means current noise is not amplified and the INA186-Q1 can drive a cleaner signal into the ADC without an output filter loading down the ADC.

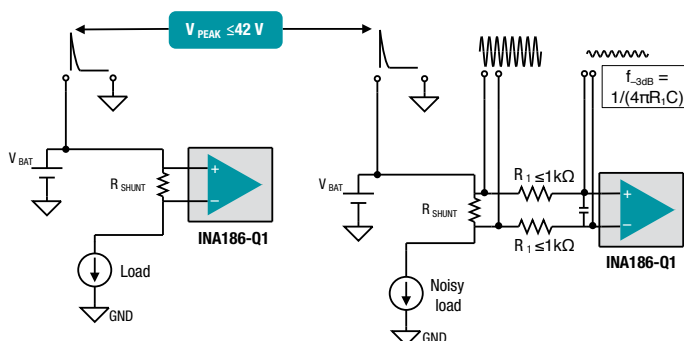


Figure 2. INA186-Q1 On 12-V Battery With and Without Noise Filtering

The breadth of the current sense portfolio enables the user to optimize tradeoffs when incorporating common input protection schemes. If the chosen device states that the Absolute Maximum Common-Mode Voltage rating cannot exceed your maximum expected voltage surge, then it needs input protection. Along with some passives, the current sensor needs transient voltage suppression (TVS) or Zener diodes at the inputs for protection. Figure 3 shows an example using the cost-optimized current sensor INA181-Q1.

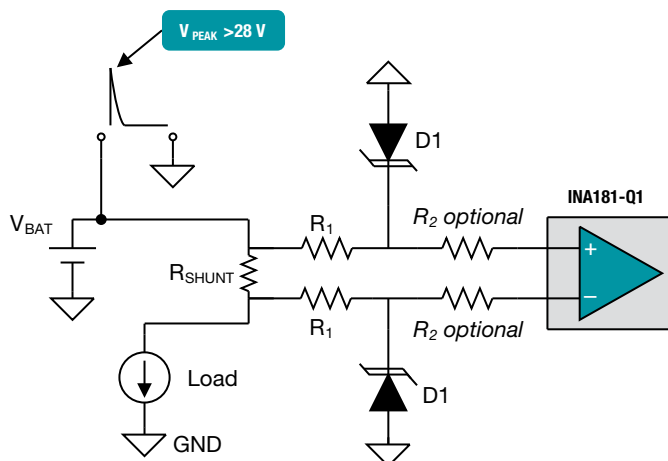


Figure 3. INA181-Q1 with Input Protection for VCM > 28 V

In Figure 3, diodes D1 clamp the input VCM of the device to less than 28 V, which is the absolute maximum for INA181-Q1. R2 is optional and can be included to prevent simultaneous turn-on for D1 and the internal ESD structure of the CSA, but it is usually not needed. If it is needed, R2 should be small compared to R1. The power rating of diodes depends on the maximum expected voltage rise, but more importantly on the turn-on current. The diode current can be reduced by increasing R1 resistance, but this reduces the effective gain of the circuit and, more critically, increases gain error variation for most current sensors (except INA186-Q1). Given the internal resistor gain network and input differential resistance of the INA181-Q1, an engineer can calculate the effective circuit gain with R1 using the equation in the [datasheet](#). Keep in mind that adding external resistors broaden the system gain error variance beyond the datasheet limits. This is due to the fact that INA181-Q1 internal resistors are matched to be ratiometric, but are not trimmed to their typical values, so their absolute values can vary by $\pm 20\%$.

Overall, an engineer can choose the INA181-Q1 because total cost with input protection is lower and increase in gain error variation is acceptable; however, devices with higher rated VCM are more straightforward solutions that provide accurate current sensing over temperature with less complexity and fewer components.

Alternate Device Recommendations

See Table 2 for applications that need either larger VCM ranges or integrated features such as shunt resistors or comparators.

Device	Optimized Parameters	Performance Tradeoff
INA253	Integrated 2 mΩ shunt resistor (included in Gain Error spec). Enhanced PWM rejection	IQ
INA301-Q1	BW and slew rate. Internal comparator with adjustable threshold and 1 μs alert response time	40 V VCM max
INA302-Q1 , INA303-Q1	BW and slew rate. Dual comparator output with adjustable thresholds and 1 μs alert response time	40 V VCM max
LMP8278Q-Q1	-12 V to +50 V VCM survivability. Adjustable gain and filtering. Buffered output	VOS
INA1x8-Q1 , INA1x9-Q1	≥60 VCM. Current output (adjustable gain). Trimmed input resistors. Low IB when powered off	VOS

Table 2. Alternate Device Recommendations

TIDA-00302	Transient Robustness for Current Shunt Monitor
SBOA162	Measuring Current To Detect Out-of-Range Conditions
SBOA165	Precision current measurements on high-voltage power-supply rails
SBOA167	Integrating the Current Sensing Signal Path
SBAA324	Shunt-based Current-Sensing Solutions for BMS applications in HEVs and EVs

Table 3. Related Technical Documentation

Simplifying voltage and current measurements in battery test equipment

Battery test equipment verifies battery pack functionality and performance before shipment to customers. There are three major functional tests that a battery tester perform:

- Formation and grading of batteries. After the battery cell or battery pack is assembled, each unit must undergo at least one fully controlled charge or discharge cycle to initialize the device and convert it to a functional power storage device. Battery vendors also use this process to grade battery cells, which is the process of separating the cells into different performance groups according to target specifications. For a more in-depth look at a battery initialization circuit, see [the Bi-Directional Battery Initialization System Power Board Reference Design](#).
- The loop and feature test. The loop and feature test refers to cycling the battery cell or battery pack through repeated charging and discharging sequences. This verifies that the battery's characteristic life and reliability parameters are within the specified range of the defined tolerances.
- The function test. Functional testing verifies that the battery pack is operational before shipment and assures that each battery cell and battery pack is working properly.

In typical systems, a buck converter is used as the power source for battery charging and a boost converter is used for battery discharge. Both conventional operational amplifiers (op amps) and instrumentation amplifiers (INAs) are used in the feedback loop to control both the charging and discharging of voltage and current.

To charge the battery, the buck converter is enabled while the first-stage voltage op amps and current-sense INA measure the battery voltage and charging current of the battery cell or battery pack. These conditioned signals serve as the input to the second-stage error op amp for either the voltage loop or current loop, respectively.

The gained-up output from each error op amp serves as the input to the third-stage buffer op amp. The output of the buffer op amp feeds into the feedback pin of the buck converter to control the output voltage or current. Depending on the output current requirements, the buck-boost functions can be accomplished several ways; however, two approaches are the most common.

For higher-current requirements, you can use an integrated charge controller and external field-effect transistor (FET). However, for lower-current requirements, which are common in cost-sensitive systems, you can implement this function discretely, as shown in **Figure 2**. Just adjust V_{V_ref} and V_{I_ref} on the positive input pins of the error op amps to adjust the target output voltage and current of the buck converter to the optimal value. In a typical battery-charging application, the output voltage of the current-loop error op amp starts high, putting the buck converter into a constant current output.

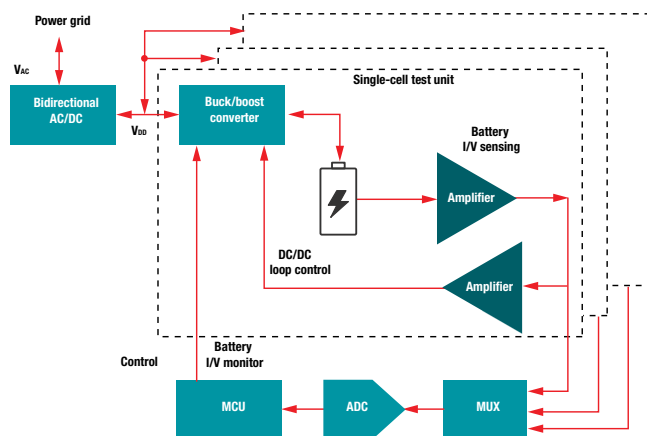


Figure 1: Traditional battery test equipment block diagram

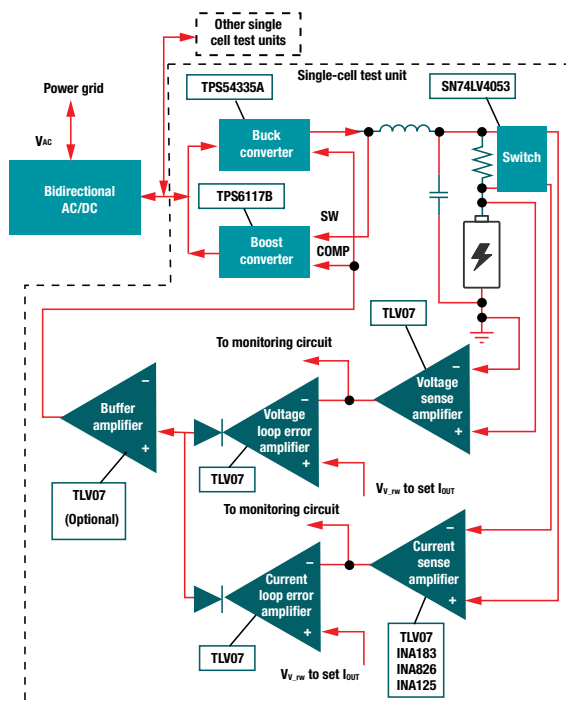


Figure 2: Battery test equipment typical amplifier configuration

In the next phase, the output voltage of the voltage-loop error op amp goes high, putting the buck converter into a constant voltage output. When the battery is discharging, the boost converter is enabled. The op amps control the battery discharge current and voltage, functioning in the same manner as they do when the battery is charging. The boost converter boosts the battery voltage to VDC, which is usually 12 V.

The typical system requirements are:

Regulated current error $ERR_{I_{OUT}} = 0.1\%$.

Regulated voltage error $ERR_{V_{OUT}} = 0.5\%$.

To achieve these requirements, you'll need an op amp with a low offset voltage (VOS), a low VOS temperature drift and a high common-mode rejection ratio (CMRR) like the [TLV07](#).

The op amps create a closed loop with the power stage. The voltage on the inverting input of the error op amp will be very close to the reference voltage V_{W_ref} and V_{I_ref} , thus minimizing the error from the large loop gain. Since the major errors come from the voltage- and current-sense amplifiers, it's important to select high-precision amplifiers.

For example, if the desired regulated output current target I_{SET} is 10 A, and the current-sense resistor R_{SENSE} is 20 mΩ, the input error of the amplifier will be, shown in **Equation 1**:

$$V_{I_ERR_RTI} < ERR_{I_{OUT}} \times I_{SET} \times R_{SENSE} = 200 \mu V$$

If the desired regulated output voltage is set to V_{SET} 4.2 V, the input error of the amplifier will be, shown in **Equation 2**:

$$V_{V_ERR_RTI} < ERR_{V_{OUT}} \times V_{SET} = 21 mV$$

Assuming that the temperature rises from 25°C to 85°C and the battery voltage is 4V, you can easily calculate the real-world error from low-offset and low-offset-drift op amps such as the TLV07, as shown in **Equation 3**.

$$\begin{aligned} V_{TLV07_ERR_RTI} &= V_{OS_max} + dV_{OS} / dT_{max} \times 60^\circ C + 4 V / CMRR_{DC} \\ &= 100 \mu V + 0.9 \mu V / ^\circ C \times 60^\circ C + 4 V / 158489 \\ &= 154 \mu V < V_{I_ERR_RTI} \text{ and } V_{V_ERR_RTI} \end{aligned}$$

For our next example, let's use an INA that integrates all of the feedback resistors, delivers a $V_{OS_max} = 150\mu V$ and a $dV_{OS}/dT_{max} = 0.5\mu V/^\circ C$, and is a good fit for performing the current-shunt amplifier function in a system with a simplified design.

If the system requires even higher performance specifications, you can change the current and voltage errors to 0.05% and 0.1%, respectively. In this case, you can use a precision INA such as the zero-drift INA188. Assuming the same conditions from the first example, with a 60°C temperature rise and a V_{BAT} of 4V, the real-world error from the INA188 is:

- $V_{I_ERR_RTI} = 67 \mu V$.
- $V_{V_ERR_RTI} \leq 4.2 mV$.

Looking at **Figure 3**, the I+ and I- contributions are a result of the current-sense resistors. The B+ and B- components are from the positive and negative terminals of the battery. Since the actual battery voltage may be higher than 5 V, the typical op amp power supply is 12 V. The TLV07, [INA188](#) and [INA125](#) all have a 36V maximum (± 18 V) supply voltage, meeting system requirements.

Because the battery current can be close to zero during charge and discharge cycles, implementing a bipolar supply in the first-stage current-sensing op amp avoids clipping the current-sense signal. Type-III compensation is applied on each stage of the error op amp, with R12, C3 and C4 and R6, C1 and C2, respectively. To assure loop stability, you should fine-tune these values based on the actual power-supply design.

Voltage and current sensing are the two most significant measurements in battery test equipment systems. The most important device specifications for this application are devices that feature low-voltage offset and drift. These parameters are critical to assure high-performance sensing while minimizing the first-stage contribution to system error.

Device	System benefits
TLV07	Low-offset voltage and low drift provide sufficient regulated current and voltage error for cost-sensitive systems
INA125	A high CMRR of 100dB minimum increases dynamic range at the output; low offset voltage and low drift reduce the need for costly and time-consuming calibration
INA188	Low-offset voltage and zero drift provide lower regulated current and voltage errors, while a high CMRR (104dB minimum) decreases common-mode interference

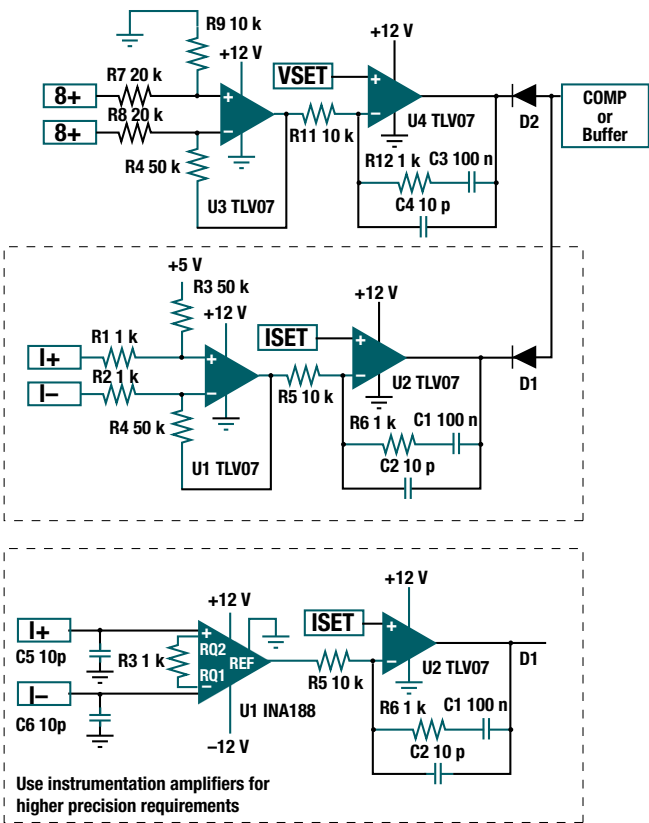


Figure 3: Voltage- and current-sense circuit with the TLV07 and INA188 in a high-end application

Chapter 2: Out-of-range current measurements

Measuring current to detect out-of-range conditions

The amount of current flowing throughout a system provides insight into how effectively the system is operating. A basic insight into the system's operation is a comparison between the current being pulled from a power supply and a pre-defined target range for that particular operating condition. Current levels exceeding the expected current level indicate that an element in the system is consuming more power than expected. Likewise, a current lower than expected may indicate that some part of the system is not powered correctly or possibly even disconnected.

There are multiple methods available to diagnose fault conditions in a system, depending on the intended use of the out-of-range indication. One method is to monitor an entire system's current consumption to identify potentially damaging excursions for the power supply. In this case, measurement accuracy is typically not critical and requires a simple alert to indicate an out-of-range condition.

Fuses are commonly used for short-circuit protection, preventing damaging levels of current from flowing in the system. In an out-of-range event, the fuse will blow and break the circuit path. The fuse must be replaced for the system to operate correctly again. In worst-case situations, the system requires delivery to a repair facility if the fuse is not easily accessible.

There is a time-current dependency that limits the effectiveness of a fuse in responding to a specific current threshold. **Figure 1** shows an example time-current response of a fuse.

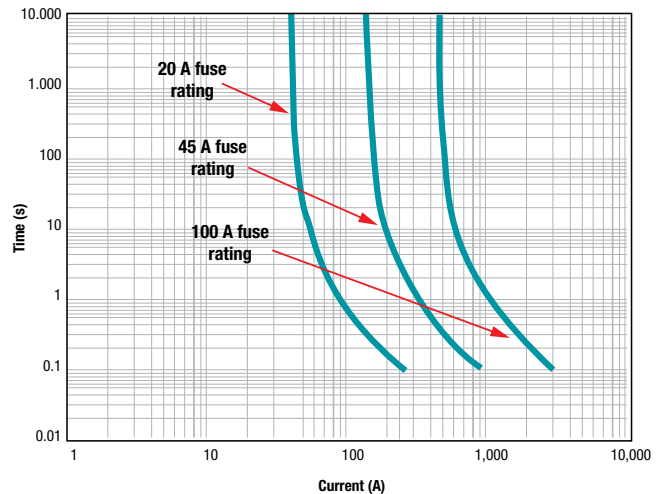


Figure 1: Typical time-current fuse curve

In another overcurrent protection scheme, the system protects itself when an excursion is detected, but returns to normal operation once the fault condition has been cleared. This protection method uses a comparator to compare the monitored operating current levels to defined thresholds, looking for out-of-range conditions. Creating the necessary level of detection for a particular application relies on system-specific variables such as the adjustability of the desired over-range threshold, the amount of margin acceptable in the threshold level and how quickly the excursion must be detected.

The [INA381](#) is a specialized current-sense amplifier with an integrated stand-alone comparator with the ability to perform the basic comparisons to the expected operating thresholds required for out-of-range detection.

Figure 2 shows the INA381 measuring the differential voltage developed across a current-sense resistor and the comparison to a user-adjustable threshold level. The alert output pulls low when the threshold level is exceeded. The INA381's alert response can follow a current excursion as quickly as 10 μ s later.

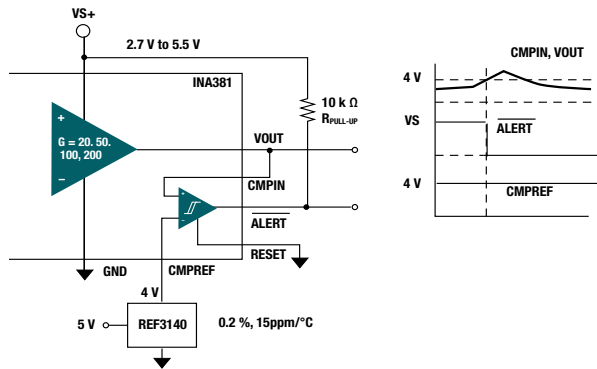


Figure 2: INA381 overcurrent comparator

There may also be a need to provide information about how much current the supply is actually pulling or a particular load in addition to the fault indication. With these requirements, a typical approach is to use a combination of a current-sense amplifier and a stand-alone comparator, as shown in **Figure 3**.

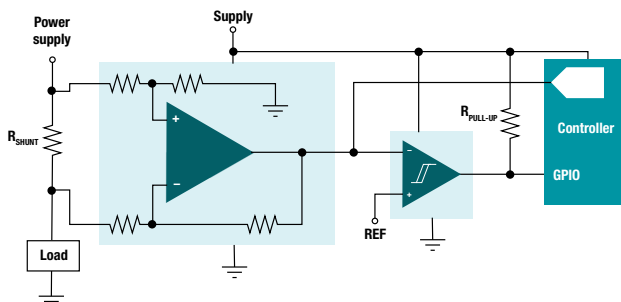


Figure 3: Discrete overcurrent detection

The current-sense amplifier measures the differential voltage developed across the sense resistor and sends the output to both the comparator input and to the analog-to-digital converter (ADC).

The [INA301](#) combines both the current-sense amplifier (providing a voltage output signal proportional to the measured input current) and an on-board comparator (for overcurrent detection) in one device, as shown in **Figure 4**.

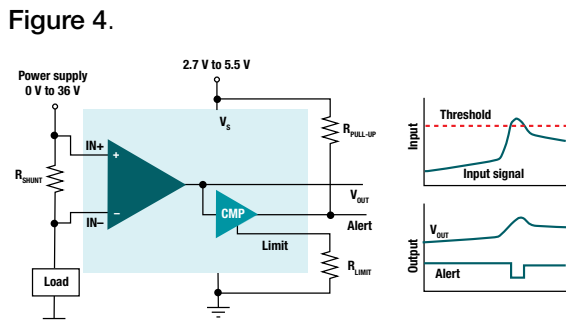


Figure 4: INA301 integrated overcurrent detection

With both the current information and an out-of-range indicator, the system may use multiple monitoring and protection schemes based on the operating conditions. One scheme used with the INA301 is to initially monitor only the alert indicator as a fault indicator. Upon the detection of an out-of-range condition and the assertion of the alert pin, the system begins actively monitoring the analog output-voltage signal, allowing the system to respond accordingly. The system response will typically be to reduce system performance levels, shut down entirely or continue monitoring to determine if the excursion will become a more significant concern. Having both the proportional output voltage as well as the on-board overcurrent detection function enables the system to only actively monitor the current information when necessary, optimizing system resources.

The INA301 amplifier has a small signal bandwidth of 450 kHz at a fixed gain of 100 (gains of 20 and 50 are also available) and a maximum input offset voltage of 35 μ V. In addition to the maximum gain error specification of 0.2%, the amplifier's ability to detect the out-of-range condition is fast. The INA301 is able to achieve accurate input measurements and quickly respond to overcurrent events with a less than 1 μ s response time that includes the input signal measurement, a comparison to the user-selected alert threshold and an assertion of the comparator's output.

Alternative device recommendations

For applications where you need to monitor current on voltage rails that are higher than the INA301's range of 36 V with the onboard overcurrent detection, use the INA200.

The INA180 is a current-sense amplifier commonly used in a discrete overcurrent detection circuit using an external comparator.

For applications requiring monitoring of a second fault threshold level, the INA302 features an additional out-of-range comparator with dedicated adjustable threshold level.

Device	Optimized parameters	Performance trade-off
INA180	Packages: SC70-5, small-outline transistor (SOT) 23-5	Reduced bandwidth, analog output only
INA200	Common-mode voltage range: -16V to +80V	Reduced accuracy
INA302	Two independent alert comparators	Larger package: thin-shrink small outline package (TSSOP)-14

Table 1: Alternative device recommendations

SBOA161B	"Low-Drift, Low-Side Current Measurements for Three-Phase Systems"
SBOA163A	"High-Side Motor Current Monitoring for Over-Current Protection"
SBOA167A	"Integrating the Current Sensing Signal Path"
SBOA168B	"Monitoring Current for Multiple Out-of-Range Conditions"
SBOA193	"Safety and Protection for Discrete Digital Outputs in a PLC System Using Current Sense Amplifiers"

Table 2: Related TI application notes

Monitoring current for multiple out-of-range conditions

One of the first parameters to look at when determining the proper operation of a printed circuit board (PCB) design is the operating current. By examining the operating current, you can immediately tell if something on the board is shorted, whether any of the devices are damaged or (in some cases) whether the software is running as expected. The traditional approach of using a current-sense amplifier plus an analog-to-digital converter (ADC) to monitor current for out-of-range conditions does not provide the required alert response time. Also, the use of an ADC to monitor overcurrent alert thresholds requires constant communication between the ADC and the host processor, which can unnecessarily burden the system.

To address the response time required for out-of-range current conditions, you need analog comparators to detect when the current exceeds a given reference threshold. In many cases, however, having only one alert level is insufficient to determine the system status and provide appropriate system responses to out-of-range currents. To handle this requirement, the circuit shown

in **Figure 1** can monitor multiple out-of-range current conditions.

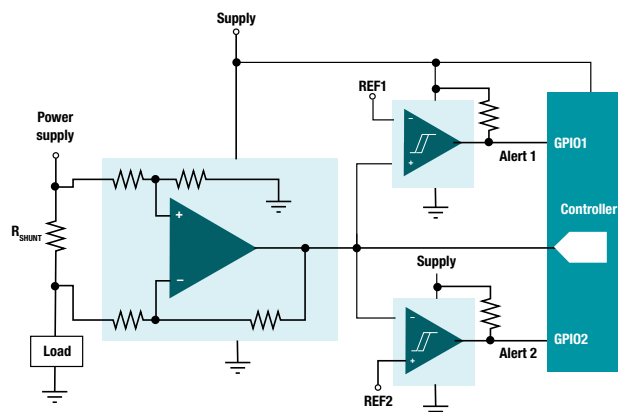


Figure 1: Discrete implementation to detect multiple overcurrent events

This circuit comprises five devices: a current-sense amplifier, two comparators and two references. The discrete implementation shown in **Figure 1** requires careful selection of the comparators to get the desired alert response time. Slow response times may not allow enough time for the system to take action, while too fast of a response time can trigger false alerts, possibly resulting in system shutdown. **Figure 2** shows a simpler circuit that addresses the design issues present in the discrete implementation.

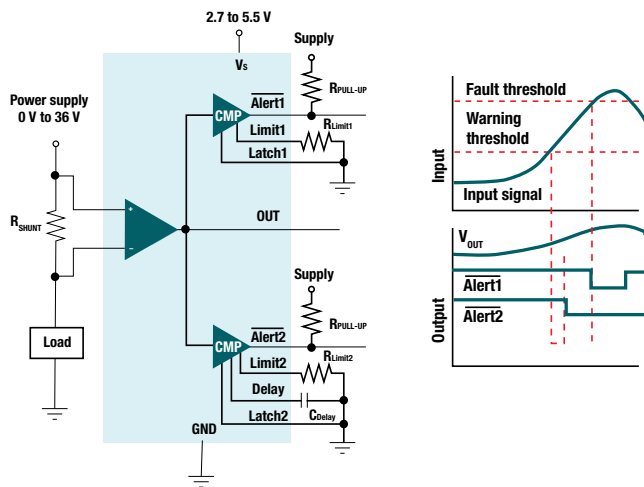


Figure 2: INA302 multivalent overcurrent comparator

The [INA302](#) incorporates the ability to detect two out-of-range conditions. The lower out-of-range condition is known as the overcurrent warning threshold, while the higher out-of-range condition is known as the overcurrent fault threshold. The overcurrent warning threshold enables detection when the current is starting to get too high but has not yet reached the fault threshold at which a system shutdown may initiate. When the current exceeds the warning threshold, the system may opt to reduce the system power consumption by disabling sub circuits, controlling supply voltages or reducing clocking frequencies to lower the total system current and prevent a fault condition. If an overcurrent fault condition does occur, it is important to respond quickly to prevent further system damage or malfunctioning behavior.

To minimize the component count and facilitate ease of use, the alert thresholds of the INA302 are set with single external resistors. The fault threshold should be set higher than the worst-case current the system could be expected to consume. When the current exceeds this threshold, the alert pin of the INA302 will respond within 1 μ s. The value for the warning threshold is application-dependent, but is usually higher than the nominal operating current. The response time of the warning threshold is adjustable with an external capacitor from 3 μ s to 10 s.

By setting the warning threshold delay time appropriately, it is possible to set the overcurrent warning threshold closer to the maximum DC operating current while still avoiding false trips caused by brief current spikes or noise. Wider separation between the fault and warning thresholds gives the system additional time for preventive action before the fault threshold is exceeded.

Some systems allow operation above the warning threshold for a period of time before triggering an alert. One such application is monitoring the supply current to a processor. The processor may be allowed to operate above the normal maximum current level for a brief period of time to maximize computing throughput during critical operations. If the current is above the warning threshold when the set delay expires, the alert output will pull low to notify the host processor so that the voltage or clocking frequency can decrease before overheating occurs.

In some systems, it is beneficial to detect when the current is too low. For these applications, the [INA303](#) shown in **Figure 3** provides both over- and undercurrent detection.

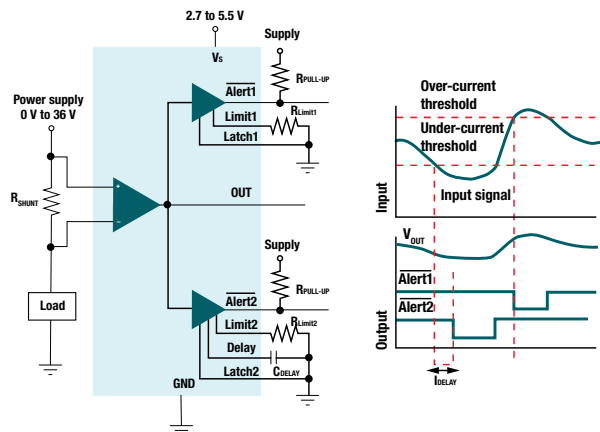


Figure 3: INA303 over- and undercurrent detection

When the current exceeds the overcurrent fault threshold, the ALERT1 output will respond within 1 μ s. However, if the current goes below the undercurrent threshold, the ALERT2 response time is set by the delay capacitor. Undercurrent situations may briefly occur in normal operation. However, if the undercurrent condition lasts longer than expected, it could be due to a

damaged device or a system that is about to fail. In this case, the alert output can notify the system controller of this condition and fault handling procedures can be implemented before system failure.

Another use of undercurrent detection is to provide confirmation about proper system status. Some systems go into low-power modes where the current is below the normal operating range. In this case, the undercurrent alert output can notify the host that the system has

indeed entered a shutdown state.

In some designs, notification is only necessary if the current is outside of expected operating bounds. For these cases, the INA303 can be configured to run in window mode by connecting the two alert outputs together, as shown in **Figure 4**. In this mode, the single alert output will be high as long as the current is within the normal operating window.

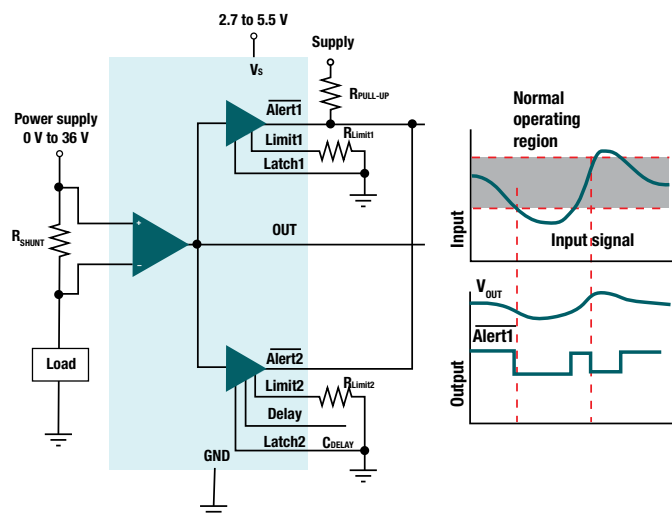


Figure 4: INA303 window mode operation

Alternative device recommendations

The INA226 can be used in applications that require digital current monitoring. If you need only a single digital alert output, the INA300 is available in a tiny 2mm-by-2mm quad flat no-lead (QFN) package.

For applications that only require a single alert output in addition to the analog current signal, the INA301 provides excellent current-monitoring accuracy with an alert response less than 1 μ s.

Device	Optimized parameters	Performance trade-off
INA226	Digital current monitor	Reduced accuracy
INA300	2mm-by-2mm QFN package	Single alert
INA301	Mini small outline package (MSOP)-8, single alert with analog monitor	Single alert
INA381	Current sensor with integrated stand-alone comparator in small 2mm by 2mm package	Single alert

Table 1: Alternative device recommendations

SBOA162C	"Measuring Current to Detect Out-of-Range Conditions"
SBOA163A	"High-Side Motor Current Monitoring for Over-Current Protection"
SBOA167A	"Integrating the Current Sensing Signal Path"

Table 2: Related TI application notes

High-side motor current monitoring for overcurrent protection

High-power precision motor systems commonly require detailed feedback such as speed, torque and position to be sent back to the motor-control circuitry in order to precisely and efficiently control the motor's operation. Simpler motor-control applications, such as fixed-motion tasks, may not require the same level of precision system feedback as they may only need to know if the system has encountered an unintended object in its path or there is a short in the motor's winding. More complex motor-control systems implementing dynamic control and active monitoring can also benefit from adding a simple out-of-range detection function because of the faster indication of out-of-range events.

By placing a current-sense amplifier in series with the DC power supply driving the high side of the motor-drive circuitry – as shown in **Figure 1** – it's possible to easily measure the overall current to the motor in order to detect out-of-range conditions. To detect small leakages, you can also measure the low-side return current. A difference between the high- and low-side current levels indicates the existence of a leakage path within the motor or motor-control circuitry.

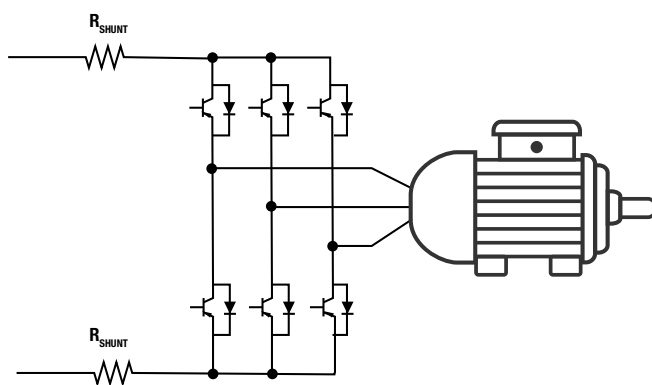


Figure 1: Low- and high-side current sensing

The DC voltage level varies depending on the voltage rating of the motor, leading to multiple current-measurement solutions to accommodate the corresponding voltage levels. For low-voltage motors (~5V), the selection of circuitry to monitor this current is

much simpler, because multiple amplifier types (current sense, operational, difference, instrumentation) can perform the current-measurement function and support this common-mode input-voltage range.

For larger-voltage motors (24 V and 48 V, for example), the available options decrease to dedicated current-sense and differential amplifiers. As the voltage requirements continue to increase, measurement errors begin to impact the ability to effectively identify out-of-range conditions.

One specification that describes an amplifier's effectiveness at operating at high input-voltage levels is the common-mode rejection (CMR) term. This specification directly describes how well an amplifier's input circuitry can reject the influence of large input voltages. Ideally, an amplifier can completely reject and cancel out any voltage common to both input pins and amplify only the differential voltage that exists between them. However, as the common-mode voltage increases, leakage currents in the amplifier's input stage result in an additional input offset voltage. Larger input-range levels will create proportionally larger measurement errors.

For example, an amplifier (difference or current sensing) that has a CMR specification of 80dB will have a significant offset voltage introduced in the measurement based on the input-voltage level. An 80dB CMR specification corresponds to an additional 100 μ V of offset voltage induced into the measurement for every volt applied to the input.

Many devices are specified under defined conditions (common-mode voltage [VCM] = 12V and voltage supply (VS) = 5 V, for example), which establishes the baseline for the default specifications (CMR and power-supply rejection ratio [PSRR], specifically). For example, operating at a 60 V common-mode voltage creates a change in VCM of 48V (60 V-12 V). A 48 V change with an 80 db CMR results in an additional 4.8mV of offset voltage in addition to the specified input offset voltage found in the device's data sheet.

This additional induced offset voltage does not significantly impact applications employing calibration schemes. However, for applications where system calibration cannot account for this shift in offset, selecting an amplifier with better VCM rejection is essential.

The [INA240](#) is a dedicated current-sense amplifier with a common-mode input-voltage range of -4 V to +80 V and a worst-case CMR specification of 120dB over the entire input and temperature range of the device. 120dB of CMR corresponds to an additional 1 μ V of input offset voltage induced for every 1V change in common-mode voltage. The temperature influence on the amplifier's ability to reject common-mode voltages is not well documented in many product data sheets, so you should evaluate it in addition to the room-temperature specification.

The INA240 maintains a guaranteed 120 dB CMR specification over the entire -40°C to +125°C temperature range. The typical CMR performance for the INA240 over the entire temperature range is 135dB (less than 0.2 μ V for every 1 V change), as shown in **Figure 2**.

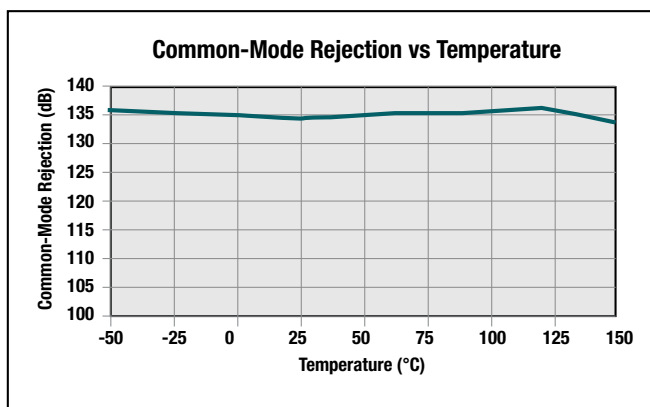


Figure 2: Common-mode rejection vs. temperature

A system controller has the ability to use the current-sense amplifier's measurement to evaluate the operation of the system. Comparing the current information to a predefined operating threshold enables the detection of out-of-range events. A comparator following the high-side current-sense amplifier can easily detect

and provide alerts quickly to the system, allowing for corrective actions.

Figure 3 illustrates the signal-chain path for monitoring and detecting out-of-range excursions when measuring currents on a high-voltage rail driving motor-drive circuitry. The output signal proportional to the measured input current is directed to the ADC and also sent to the comparator to detect overcurrent events. The comparator alert will assert if the input current level exceeds the predefined threshold connected as the comparator's reference voltage.

A key requirement for overcurrent detection circuitry is the ability to detect and respond quickly to out-of-range conditions. A signal bandwidth of 100 kHz and 2V/ μ s enables the INA240 to – in the span of a few microseconds – accurately measure and amplify the input current signal and send the output to the high-speed comparator for the issue of an alert based on a shorted condition. This fast response time ensures that unintended excess current flowing in the system will not damage other critical system components.

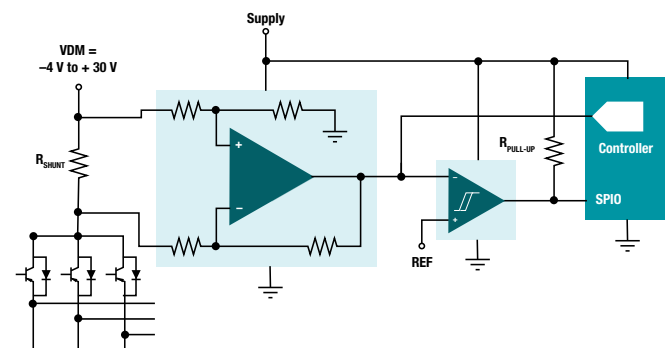


Figure 3: High-side overcurrent detection

Alternative device recommendations

You can use the LMP8640HV for applications measuring high-voltage capability that need a faster signal bandwidth or a smaller package.

For applications requiring a higher voltage capability, the INA149 is a high-performance difference amplifier capable of interfacing with common-mode voltages up to ± 275 V off of a ± 15 V supply and has a guaranteed CMR of 90 dB (or 31.6 μ V for every 1 V input change).

The INA301 is a precision current-sense amplifier with an onboard comparator that can detect overcurrent events on common-mode voltages up to 36 V.

Device	Optimized parameters	Performance trade-off
LMP8640HV	Package: small-outline transistor (SOT) 23-6, signal bandwidth	Accuracy
INA149	VCM range: ± 275 V	CMR, gain
INA301	Onboard comparator: 35 μ V offset voltage	VCM: 0V to 36 V

Table 1: Alternative device recommendations

SBOA160B	"Low-Drift, Precision, In-Line Motor Current Measurements with Enhanced PWM Rejection"
SBOA161B	"Low-Drift, Low-Side Current Measurements for Three-Phase Systems"
SBOA162C	"Measuring Current to Detect Out-of-Range Conditions"
SBOA165B	"Precision Current Measurements on High-Voltage Power Supply Rails"

Table 2: Related TI application notes

Chapter 3: Current sensing in switching systems

Low-drift, precision, in-line motor current measurements with enhanced PWM rejection

The demand for higher-efficiency systems continues to increase, leading to direct pressure for improvements in motor operating efficiency and control. This focus applies to nearly all classes of electric motors, including those used in white goods, industrial drives and automotive applications.

To ensure that a motor is operating at its peak efficiency, its operational characteristics that are fed back into the control algorithm are critical. Phase current is one of these critical diagnostic feedback elements used by the system controller to enable optimum motor performance.

Due to the continuity of the measurement signal and direct correlation to the phase currents, an ideal location to measure the motor current is directly in-line with each phase, as shown in **Figure 1**. Measuring current in other locations, such as the low side of each phase, requires recombination and processing before the control algorithm can use meaningful data.

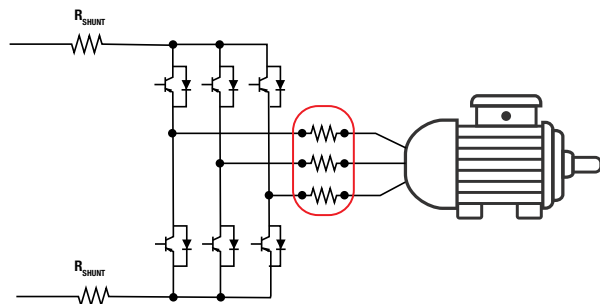


Figure 1: In-line current sensing

The drive circuitry for the motor generates pulse-width modulated (PWM) signals to control the motor's operation. These modulated signals subject the measurement circuitry placed in-line with each motor phase to common-mode voltage (VCM) transitions that can switch between large voltage levels over very short time periods. A perfect amplifier would have the

ability to completely reject the VCM component of the measurement and only amplify the differential voltage corresponding to the current flowing through the shunt resistor. Unfortunately, real-world amplifiers are not ideal and are influenced by the large PWM-driven input-voltage steps. Because real-world amplifiers do not have infinite common-mode rejection, large, unwanted disturbances can potentially appear at the amplifier output corresponding to each input-voltage step, as shown in **Figure 2**. These output disturbances, or glitches, can be very large and take significant time to settle following the input transition – depending on the characteristics of the amplifier.

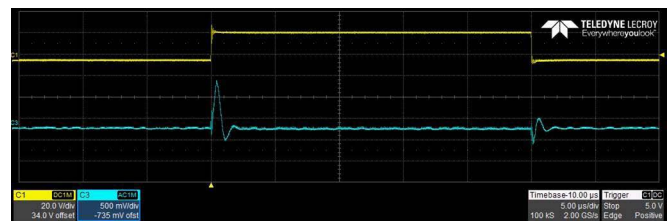


Figure 2: Typical output glitch from a large-input VCM step

A common approach to this measurement is to select a current-sense amplifier with a wide bandwidth. In order to stay above the audible frequency range, the typical modulation frequencies range from 20 kHz to 30 kHz. Amplifier selection for making in-line current measurements in these PWM-driven applications targets amplifiers with signal bandwidths in the 200 kHz to 500 kHz range. Amplifier selection was not historically based on actual signal bandwidths, which are significantly lower than the PWM signal. Selecting higher amplifier bandwidths enables the output glitch to settle quickly following an input-voltage transition.

The [INA240](#) is a high-common-mode, bidirectional current-sense amplifier designed specifically for these types of PWM-driven applications. This device approaches the problem of measuring a small differential voltage in the presence of large common-mode voltage

steps by using integrated enhanced PWM rejection circuitry to significantly reduce the output disturbance and settle quickly. Standard current-sense amplifiers rely on a high signal bandwidth to allow the output to recover quickly after the step, while the INA240 features a fast current-sense amplifier with internal PWM rejection circuitry to achieve an improved output response with reduced output disturbance.

Figure 3 illustrates the improved response of the INA240 output due to this internal enhanced PWM rejection feature.

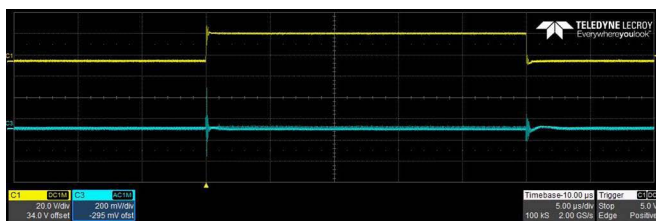


Figure 3: Reduced output glitch by enhanced PWM rejection

For many three-phase applications, there are few requirements related to the accuracy of this in-line current measurement. A limited output glitch is necessary to prevent false overcurrent indications, in addition to having an output that quickly responds to ensure sufficient control of the compensation loop. For other systems, such as electronic power steering (EPS), precise current measurements are necessary to provide the required feedback control to the torque assist system.

The primary objectives in an EPS system are to assist with additional torque to the driver's applied torque on the steering wheel and to provide a representative feel in the steering response corresponding to driving conditions. Phase-to-phase current-measurement errors can become very noticeable in this tightly controlled system. Any unaccounted-for variance between phases leads directly to increased torque ripple that is perceptible to the driver through the steering wheel. Reducing measurement errors, especially those induced by temperature, is critical to maintain accurate feedback control and deliver a seamless user experience.

Common system-level calibration frequently reduces the reliance on an amplifier's performance at room temperature to provide precise measurement accuracy. However, accounting for parameter shifts such as input offset voltage and gain error as the operating temperature varies is more challenging. Good temperature compensation schemes are based on a characterization of the amplifier's performance variation over temperature and rely on a consistent and repeatable response to external conditions from system to system. Improving the capability of the amplifier to remain stable with minimal temperature-induced shifts is ideal to reduce the need for complex compensation methods.

The INA240 features a 25 μV maximum input offset voltage and a 0.20% maximum gain error specification at room temperature. For applications requiring temperature stable measurements, the device's input offset voltage drift is 250 $\text{nV}/^\circ\text{C}$ with a 2.5 $\text{ppm}/^\circ\text{C}$ amplifier gain drift. Even as the operating temperature varies over the system's entire temperature range, the measurement accuracy remains consistent. Combining the measurement temperature stability, wide dynamic input range and most importantly enhanced PWM input rejection, the INA240 is a good fit for PWM-driven applications requiring accurate and reliable measurements for precisely controlled performance.

Alternative device recommendations

The INA282 is able to measure very precise large common-mode voltages that don't change as quickly as what's typical for PWM driven applications, so you can use it in high-voltage DC applications.

The LMP8481 is a bidirectional current-sense amplifier used for high common-mode voltages that do not require the amplifier to include ground within the input-voltage range.

Device	Optimized parameters	Performance trade-off
INA282	Common-mode input range: -14V to +80V; mini small-outline package (MSOP)-8	Low bandwidth, good for DC applications
LMP8481	Low power: 155 μ A; MSOP-8	Common-mode input range: 4.5V to 76V; lower accuracy

Table 1: Alternative device recommendations

SBOA161B	“Low-Drift, Low-Side Current Measurements for Three-Phase Systems”
SBOA162C	“Measuring Current to Detect Out-of-Range Conditions”
SBOA163A	“High-Side Motor Current Monitoring for Over-Current Protection”
SBOA165B	“Precision Current Measurements on High-Voltage Power Supply Rails”

Table 2: Related TI application notes

High-side drive, high-side solenoid monitor with PWM rejection

A solenoid is an electromechanical device made up of a coil that’s wound around a movable iron material called an armature or plunger. Electric current passing through the coil generates a magnetic field, causing the armature to travel over a fixed range. **Figure 1** is an illustration of an electromechanical solenoid.

You’ll often find solenoids in simple on/off applications like relays that require only two states of operation, or for linear operation where the current is proportional to the position of the armature. Linear solenoids are used in equipment that needs to precisely regulate pressure, fluid flow (like industrial applications) or air flow (like critical medical applications). In automotive applications, linear solenoids are used in fuel injectors, transmissions, hydraulic suspension and even for haptic effects.

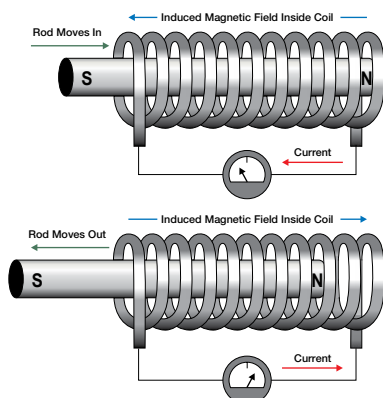


Figure 1: Electromechanical solenoid construction

Multiple configurations exist for connecting and driving solenoids. One common approach uses a high-side driver configuration in which the current-sense amplifier is connected between the high-side switch and the solenoid, as shown in **Figure 2**. One benefit to this configuration is that the solenoid is isolated from the battery voltage when the high-side switch is off. Eliminating the solenoid’s continuous connection to the battery voltage reduces solenoid degradation and early lifetime failures.

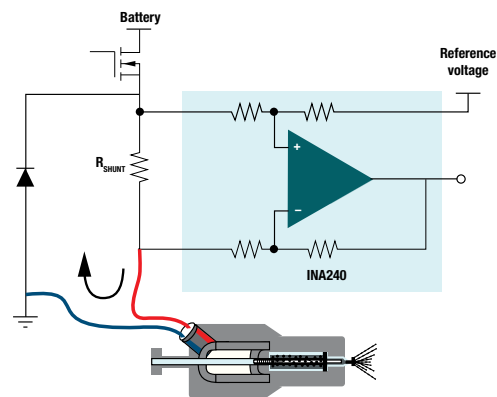


Figure 2: High-side drive with high-side current-sense amplifier

The current-sense amplifier shown in **Figure 2** must be able to reject high-common-mode dv/dt signals and support common-mode voltages that fall below ground. When the high-side switch turns on, the solenoid is energized by the current flowing from the battery. The duty cycle of the high-side switch determines the current flowing through the solenoid, which in turn controls the

travel range of the plunger. When the high-side switch turns off, the current flows through the flyback diode, forcing the common voltage to drop one diode below ground.

Solenoids and valves are highly inductive. The effective impedance of a solenoid can be simplified as resistance and inductance. The coil is constructed using copper (4,000 ppm/°C) and the effective resistance varies based on the type of solenoid, from 1Ω for haptic applications to 10Ω for linear or positional valve systems. The inductance for all solenoids ranges from 1mH to 10mH.

Figure 3 shows a current profile of a solenoid driver in open-loop mode at 25°C and 125°C. Over a 100°C rise in ambient temperature (without compensating for copper resistance), the plunger travel distance accuracy is around 40%. The solenoid current flow directly controls the plunger's travel distance. If the ambient temperature changes, the plunger's travel distance changes and affects the output control, which could be regulating pressure, fluid or air.

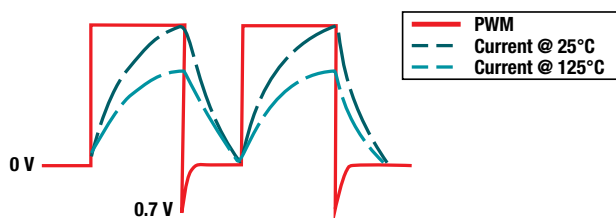


Figure 3: Solenoid current profile across temperature

By measuring current in solenoid and valve applications, it's possible to detect changes in a solenoid's operating characteristics. Through current measurement, a decrease in the magnetic field of an aging solenoid can identify faulty components before they fail. In an open-loop solenoid control system, the variation of effective impedance can drift 40% for a 100°C rise in temperature from the copper windings. Current measurement used in a current-control feedback loop

can reduce the solenoid's impedance variation over temperature from 40% down to 0.2% using the [INA240](#) current-sense amplifier.

The INA240 is a high-side, bidirectional current-sense amplifier that can support large common-mode voltages ranging from -4 V to +80 V. The INA240 is specifically designed to operate within pulse-width modulation (PWM) applications, with circuitry to suppress dv/dt signals. It lowers blanking time, enabling accurate PWM current measurements at lower duty cycles. The device's low offset voltage, drift, gain and high 400 kHz bandwidth enable accurate in-line current measurements. Valve applications that require the precise control of fluid, air and pressure will benefit from accuracy and temperature stability during current measurements.

Alternative device recommendations

If you need lower negative common-mode voltages, consider the INA193. Its -16 V input range allows for sufficient margins if larger solenoid kickback voltages are present. One of the trade-offs of the INA193 is the PWM glitch rejection and its response to quickly settle for high dv/dt signals, however.

For applications requiring higher signal bandwidths with low-input offset-voltage drifts, the LMP8640HV is another current-sense amplifier capable of supporting the requirements of a high-side drive configuration.

The LMP8278Q-Q1 is Automotive Electronics Council (AEC)-Q100 qualified, guaranteeing device specifications over an ambient temperature range from -40°C to +125°C. With common-mode voltage operation from -2 V to +40 V, you can use the LMP8278 in powertrain applications where the solenoid needs to be precisely controlled inside the chassis.

Device	Optimized parameters	Performance trade-off
INA193	Common-mode voltage range: -16V to +60V	Bandwidth, accuracy
LMP8640HV	Bandwidth: 950kHz	Slew rate, longer step-response settling
LMP8278Q-Q1	Common-mode voltage range: -2V to +40V, common-mode rejection ratio	Slew rate

Table 1: Alternative device recommendations

SBOA160B	“Low-Drift, Precision, In-Line Motor Current Measurements with Enhanced PWM Rejection”
SBOA161B	“Low-Drift, Low-Side Current Measurements for Three-Phase Systems”
SBOA163A	“High-Side Motor Current Monitoring for Over-Current Protection”
SBOA162C	“Measuring Current to Detect Out-of-Range Conditions”

Table 2: Related TI application notes

Current-mode control in switching power supplies

Most switching power supplies are designed with closed-loop feedback circuitry to provide stable power under various transient and load conditions. The feedback methodology options fall into two general categories: voltage mode control (VMC) and current mode control (CMC). Both methodologies have their strengths and weakness that determine the appropriate selection for the end-equipment application.

Control methodologies

VMC uses a scaled value of the output voltage as the feedback signal. This methodology provides a simple, straightforward feedback architecture for the control path but does have several disadvantages. The most significant disadvantage is that the output-voltage regulation requires a sensed change in the output voltage and propagation through the entire feedback signal and filter before the output is appropriately compensated. This can generate an unacceptably slow response for systems that require high levels of regulation. The feedback compensation of the supply requires a higher level of analysis to address the two poles introduced by the output low-pass filter. Additionally, the feedback component values must be adjusted since different input voltages affect the overall loop gain.

CMC addresses the VMC’s shortfalls by using the inductor current waveform for control. This signal is included with the output-voltage feedback loop as a second, fast-response control loop. The additional feedback loop does potentially increase circuit/feedback complexity, so you will need to evaluate its advantages as part of the design requirements.

By using the inductor current as part of the feedback control:

- The additional current feedback loop responds faster than when only using the output voltage for feedback control. Additionally, with the inductor current information, you can design the circuit to provide pulse-by-pulse current limiting, allowing for rapid detection and control for current-limiting needs.
- The power supply looks like a voltage-controlled current source. This permits a modular supply design to allow load sharing between multiple supplies in a parallel configuration.
- It’s possible to minimize the effects of the inductor in the control loop, since the current feedback loop effectively reduces the compensation to a single-pole requirement.

While CMC addresses some of the drawbacks of VMC, it introduces challenges that can affect circuit performance. The addition of the current feedback loop increases the

complexity of the control/feedback circuit and circuit analysis. Stability across the entire range of duty cycles and sensitivity to noise signals are other items that you need to consider in the selection of CMC. CMC breaks down into several different types of control schemes: peak, valley, emulated, hysteretic and average CMC. Let's discuss the two most common methodologies used in circuit design: peak and average CMC.

Peak CMC

Peak CMC uses the current waveform directly as the ramp waveform into the pulse-width modulation (PWM)-generation comparator instead of an externally generated sawtooth or triangle signal like VMC. The upslope portion of the inductor current or high-side transistor current waveform provides a fast response control loop in addition to the existing voltage control loop. As shown in **Figure 1**, comparing the current signal with the output of the voltage error amplifier generates the PWM control signal for the power supply.

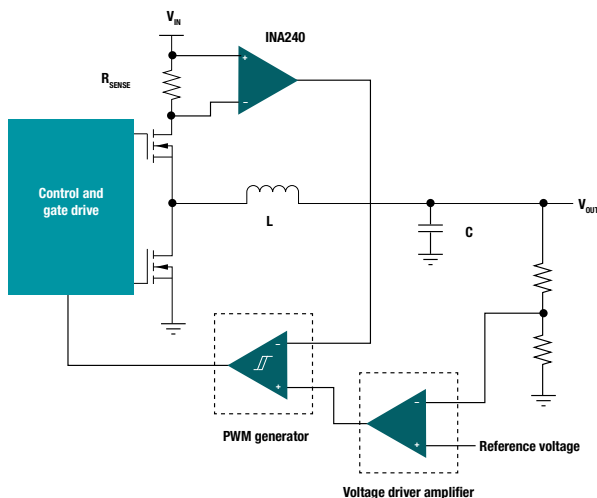


Figure 1: Block diagram of a peak CMC circuit

Switching power supplies provide high levels of efficiency between the input and output power rails. To maintain high converter efficiency, the sense resistor used to measure the inductor current should be as small as possible to reduce power loss caused by the measurement. This small-valued resistor results in a small-amplitude feedback signal.

Since the inductor current waveform is used directly as the comparator input signal, peak CMC is known to be susceptible to noise and voltage transients. Using a current-sense amplifier like the [INA240](#) with a high common-mode rejection ratio (CMRR) suppresses transients associated with PWM signals and systems. The INA240's gain flexibility enables amplification of the inductor current waveform in order to provide a larger signal for comparison without the need for additional gain or sacrificing performance. Additionally, the low offset and gain errors reduce design variations and changes across temperature.

To use peak CMC, the inductor current necessitates a high common-mode voltage measurement. The INA240's common-mode range allows for a wide range of supply input and output voltages. Peak CMC most often adds slope compensation to address stability issues with duty cycles greater than 50%. The slope compensation is added to the inductor current before use as the comparator input signal.

Average CMC

Average CMC uses the inductor current waveform and an additional gain and integration stage before comparing the signal to an externally provided ramp waveform (similar to VMC). This improves noise immunity and removes the need for slope compensation. **Figure 2** shows a block diagram of average CMC operation for a buck converter.

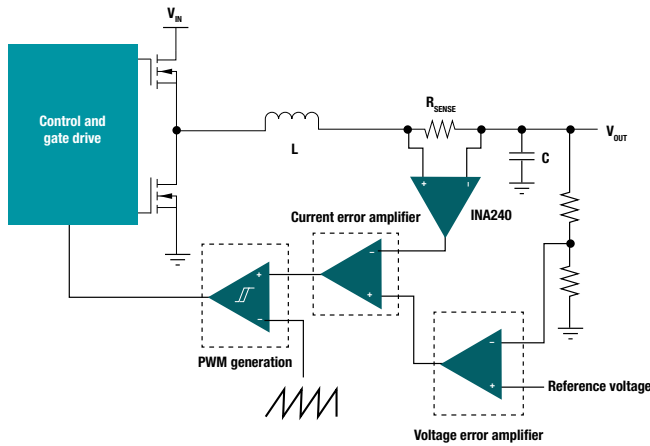


Figure 2: Block diagram of an average CMC circuit

Using average CMC improves the noise sensitivity of peak CMC to acceptable performance levels with the INA240's high CMRR, helping provide additional transient reduction. The INA240 high common-mode range is required to make the inductor current measurement and enables the use of a current amplifier in a wide range of output voltages. The INA240's high-accuracy and low-drift specifications provide consistent measurement across temperature and different assemblies.

The INA240 provides the necessary performance and features for measurement accuracy in order to maintain good signal integrity control. The INA240 features a 25 μV maximum input offset voltage and a 0.020% maximum gain error specification at room temperature. Temperature stability is important to maintain system performance, and the INA240 provides an input offset voltage drift of 250 nV/ $^{\circ}\text{C}$ with a 2.5 ppm/ $^{\circ}\text{C}$ amplifier gain drift. The INA240 features enhanced PWM rejection to improve performance with large common-mode transients and a wide common-mode input range for maximum supply output-voltage variances.

Alternative device recommendations

The INA282 allows current measurements for high common-mode voltages, making it a good fit for high-voltage DC applications that do not have PWM signals.

The LMP8481 is a bidirectional current-sense amplifier used in high common-mode voltage applications that do not require the input-voltage range of the amplifier to include ground.

Switching power-supply current measurements

There are many different switching power-supply topologies available to meet system power requirements. DC/DC switching converters reduce a higher-voltage DC rail to a lower-voltage DC rail. These converter architectures include buck, boost, buck-boost and flyback topologies. DC/AC switching converters convert a DC input voltage to an AC output voltage.

As implied by their name, switching converters employ various switches, transistors/field-effect transistors (FETs) and/or diodes to translate the input voltage to the desired output voltage at high system-efficiency levels. The switching nature of these converters presents challenges when trying to accurately measure current waveforms. Voltage-node requirements, system control requirements and measurement drift are areas to consider when selecting current-sense amplifiers.

Voltage-node requirements

Each node in the circuit architecture has a different common-mode voltage and behavior. Measuring currents at each of these locations has different characteristics that the measurement circuit must take into account.

Figure 1 illustrates the different nodes of a buck/step-down converter. The circuit shows a basic circuit consisting of a half H-bridge output stage with a low-pass filter constructed from an inductor and capacitor. The control circuitry, output stage drivers and load are not shown.

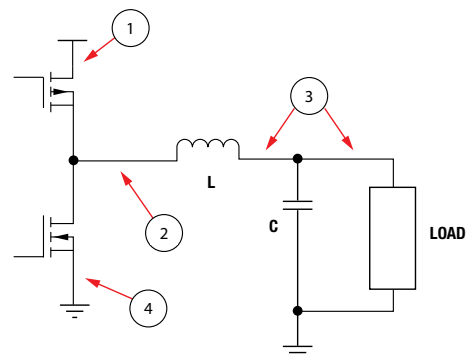


Figure 1: DC/DC switching power supply – buck architecture

Node 1's voltage is tied to the input supply of the converter. This is the high voltage that the converter is "stepping down" to the lower output voltage. Current measurements at this node are measuring the current flowing through the high-side devices of the half H-bridge and are used primarily for

overcurrent/short-circuit detection with a comparator. Any measurements made at this node require high common-mode circuits with the performance to measure a small differential voltage.

Node 2 is the midpoint of the half H-bridge and displays the pulse-width modulation (PWM) signal around which switching power supplies are based. Current measurements at this location provide the inductor current for system control and overcurrent/short-circuit detection. The voltage transitions between the upper voltage and ground (or negative supply) in the PWM ratio are averaged to produce the correct output voltage.

Node 2's voltage will have sharp common-mode transitions, so measurements here need to be able to handle the transition voltage in magnitude as well as suppressing the transient in the output waveform. Node 3's voltage is the converter output voltage, which is a DC voltage level with a small voltage ripple when observed on an oscilloscope. Measurements at this location will have similar requirements to Node 1 and provide the inductor current for use in system control and overcurrent/short-circuit detection.

Even though Node 3's voltage is less than Node 1's voltage, the desired output-voltage level may still require measurement circuitry to handle a high common-mode voltage. Node 4's voltage is tied to the ground of the circuit. This node will see low, close-to-ground

common-mode levels, so measurements at this location have a reduced set of requirements compared to the previously mentioned locations. Other DC/DC switching architectures have similar behavior to the nodes described above, although they may be at different locations in the converter circuitry.

Measurement drift requirements

Switching power supplies are highly efficient circuits for voltage-level translation, but there are still power losses in the conversion. These power losses are system efficiency losses that manifest as thermal generation or heat. Depending on the power levels of the converter, this can be a significant thermal source. The INA240 has a low thermal drift specification, which means that the current measurement does not change significantly due to heat generation. To further reduce the heat generated, the INA240 comes in different gain versions, which enable a decrease in value of the current-sense resistor. Traditional amplifiers can have significant decreases in performance as the amplifier gain increases. By contrast, all gains versions of the INA240 have excellent electrical specifications, allowing the achievement of high performance levels across different gain variants.

Table 1 compares the power dissipation difference between gains.

Parameter	Gain		
	20 V/V	100 V/V	200 V/V
Input voltage (mV)	150	30	15
RSENSE (mΩ)	15	3	1.5
Power dissipated (W)	1.5	0.30	0.15

Table 1: Power dissipation summary (full-scale output voltage = 3V and current measurement = 10A)

System control and monitoring requirements

Most switching power supplies employ closed-feedback systems to provide stable, well-regulated power. In order to provide optimized feedback control, precision measurements are necessary. Amplifier specifications, like offset and gain errors, can significantly influence the regulation ability of the control system. Different feedback methods are possible, depending on the system requirements and intended complexity of the circuitry. Additionally, system power monitoring is a growing need as designs optimize and report power consumption during different operating modes of the end equipment.

Voltage-mode feedback compares a scaled version of the output voltage to a reference voltage in order to obtain the error voltage. This feedback method is relatively simple but provides slow feedback, as the system must allow the output voltage to change before making adjustments. Current measurements for voltage-mode feedback generally monitor the load currents and determine if any short-circuits are present. The most important current-amplifier criteria for voltage-mode feedback converters is the common-mode output voltage of the converter. The output voltage on these converters ranges from low voltages used for microprocessors and low-voltage digital circuitry (1.8 V to 5 V) to high voltages used for 48V or higher systems. The output waveform, while after the filter, may still contain noise/transients that can disturb or cause errors in the measurement.

Current-mode feedback adds a feedback loop to the control system that uses the system current. The current typically used is the inductor current in the converter (see **Figure 2**). This provides a much faster internal loop to run in parallel with the voltage feedback loop. In general, one of the downsides of current-mode feedback is the susceptibility to noise/transients on the signal.

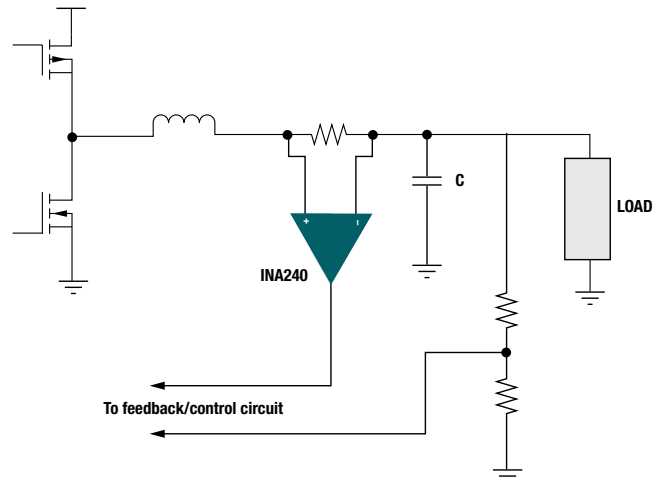


Figure 2: Current sensing for power-supply control feedback

Current-mode feedback is generally split into peak current-mode control and average current-mode control. Peak current-mode control uses the inductor current directly; therefore, any noise or transients on the signal cause disturbances in the feedback loop. The INA240 is designed with a high common-mode rejection ratio (CMRR), which helps attenuate any potential disturbances or noise from the input signal.

Alternative device recommendations

For applications requiring lower performance levels than the INA240, use the INA193 family.

The LMP8481 is a bidirectional current-sense amplifier used for high common-mode voltages that do not require the amplifier to include ground within the input-voltage range.

Device	Optimized parameters	Performance trade-off
INA193	Wide common-mode input range, small package	No enhanced PWM rejection, lower common-mode input range, reduced gain options
LMP8481	Wide common-mode input range, low power	No enhanced PWM rejection, reduced gain options, common-mode range does not include ground

Table 1: Alternative device recommendations

SBOA160B	“Low-Drift, Precision, In-Line Motor Current Measurements with Enhanced PWM Rejection”
SBOA161B	“Low-Drift, Low-Side Current Measurements for Three-Phase Systems”
SBOA169A	“Precision, Low-Side Current Measurement”
SBOA170B	“Integrating the Current Sensing Resistor”

Table 2: Related TI application notes

Using high-speed amplifiers for low-side shunt current monitoring to increase measurement bandwidth

The need to accurately and quickly detect the load current through a low-side shunt resistor is a critical application required for overcurrent protection, faster feedback control loops, accurate battery and power-supply monitoring. Load current is often measured using low-side current sensing, which is when the voltage is measured across a sense resistor placed between the load and ground. One common way to discretely implement low-side current monitoring is to use a current-sense amplifier in a difference configuration, as shown in **Figure 1**.

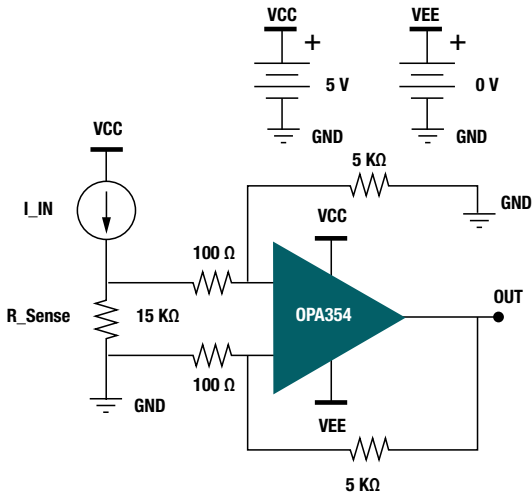


Figure 1: Low-side current-sensing test circuit using the OPA354

Low-side current-measurement applications traditionally have used a dedicated current-sense amplifier, precision amplifier or general-purpose amplifier connected to an external sense resistor. However, in applications where you need to detect small high-speed transient pulses, these devices tend to lack the adequate bandwidth needed to replicate the pulse accurately in a single gain stage.

One possible solution would be to use multiple gain stages with a lower-bandwidth device, increasing the amount of components and potentially increasing the sense resistance in order to use a smaller gain. By having a large sense resistor, you introduce noise to your signal, increase the power dissipation and cause ground disturbances.

Instead, an alternative solution would be to use a single high-speed amplifier. By using a high-speed amplifier, you have more gain bandwidth, which enables the use of a single high-gain stage with a small sense resistor. For current-sensing applications, you will want to choose an amplifier with low offset and noise so that it does not degrade the accuracy of low-voltage measurements. Consider a widely used operational amplifier (op amp) such as the OPA365. This device has a maximum input offset voltage of 200 μ V and an input-voltage noise of 4.5nV/ $\sqrt{\text{Hz}}$ at 100 kHz. An amplifier such as the OPA365 will enable the implementation of the circuit in a single

high-gain stage, save board space, keep your sense resistor low and drive the analog-to-digital converter (ADC) with a single device.

Choosing the correct amplifier will simplify the detection of high current spikes that may cause damage to the system or reduce motor and servo efficiency, all while maximizing system efficiency. There are several benefits to using a high-speed amplifier solution over the traditional method. For example, in applications such as power-supply monitoring, the duration of the pulse may be as low as 1 μ s. Without being able to detect these transients, short duration pulses may go unnoticed, causing glitches or potential damage to the rest of the system.

Figure 2 shows that with a short duration 1 μ s pulse input in a gain of 50, the OPA354 is able to reach 3 V output and replicate the original input signal much closer than a 400 kHz instrumentation amplifier or a 20 MHz bandwidth op amp. Looking at **Figure 3**, introducing a 100 nA input pulse in a gain of 50, the output response of the OPA354 is much closer than that of the INA and lower-bandwidth device.

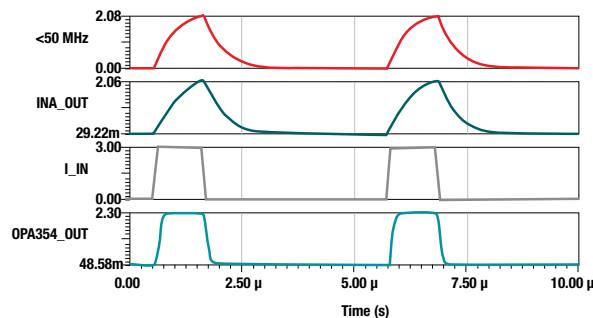


Figure 2: Output response with a 3 A 1 μ s input into 15 m Ω with a gain of 50 vs. a 400 kHz instrumentation amplifier and a 20 MHz bandwidth op amp

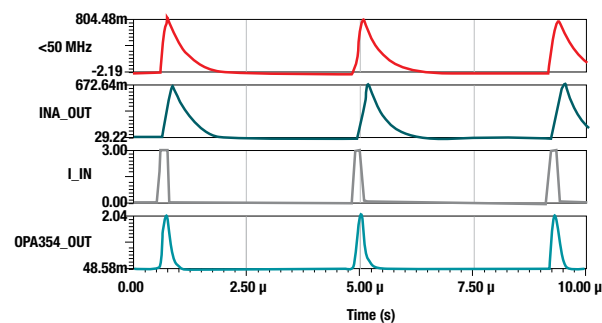


Figure 3: 100 nA pulse input into a 15 m Ω with a gain of 50 vs. a 400 kHz instrumentation amplifier and a 20 MHz bandwidth op amp

In another example, you may have a three-phase inverter sense resistor sensing large negative-phase voltages. These pulse-width modulation (PWM) duty cycles tend to be very small: around 2 μ s. The current-sense amplifier must be able to settle to <1% in this time frame and in many cases will drive an ADC for maximum system performance. In applications such as three-phase inverters, you want maintain low distortion at the maximum rate at which the output will change with respect to time. In general, high-speed amplifiers offer slew rates >25 V/ μ s and fast settling times of <0.5 μ s, making them a good choice when you have a high rate of change in the output voltage caused by a step change on the input in the form of short current pulses.

Given the high-slew-rate, larger-bandwidth and fast-settling high-speed amplifiers contribute to keeping the detection time down to a few microseconds. By using a high-speed amplifier for motor control applications, you can get a fast and precise current measurement for the best dynamic motor control, minimum torque ripple and minimum audible noise.

Traditionally, when using an op amp to measure a small differential voltage signal from the shunt resistor, you will want to make sure that the op amp has enough bandwidth to make a precise and accurate measurement without introducing error to the signal for maximum system efficiency. Measuring short duration pulses can be a challenge, but by using a high-speed amplifier you have high slew rates and plenty of bandwidth with which to track the input signal.

Alternative device recommendations

For applications that need similar performance to the OPA365 but higher bandwidth and slew rates, the OPA836 family offers a slew rate of 560 V/ μ s with a gain bandwidth product of 120 MHz.

For applications requiring OPA365 performance but higher supply ranges, the LMH661x family offers supply maximums up to 12.8 V. For more alternative devices, check out Table 1.

Device	Optimized parameters	Performance trade-off
OPA836	Higher bandwidth, lower power consumption	Input to -V rail, slightly less output current
OPA354	Higher bandwidth, higher slew rate, higher output current	Slightly higher offset and power consumption
LMH6618	Higher supply maximum, higher bandwidth, lower Iq	Slightly higher noise and less output current
LMH6611	Higher supply maximum, higher bandwidth, higher slew rate	Input to -V rail, slightly more power consumption

Table 1: Alternative device recommendations

TIDA-00778	"Low-Drift, Precision, In-Line Motor Current Measurements with Enhanced PWM Rejection"
TIDA-01418	"Low-Drift, Low-Side Current Measurements for Three-Phase Systems"

Table 2: Alternative Technical Collateral

Chapter 4: Integrating the current-sensing signal chain

Integrating the current-sensing signal path

In electronic systems, current measurements provide feedback to verify that operation is within acceptable margins and detect any potential fault conditions. Analyzing a system's current level can diagnose unintended or unexpected operating modes, enabling adjustments that can improve reliability or protect system components from damage.

Current is a signal that is difficult to measure directly. However, there are several measurement methods capable of measuring the effect of flowing current. Current passing through a wire produces a magnetic field that is detectable by magnetic sensors (Hall-effect and fluxgate sensors, for example). It's also possible to measure current by measuring the voltage developed across a resistor as current passes through. This type of resistor is called a current-sense or shunt resistor.

For current ranges reaching up to 100A on voltage rails below 100 V, measuring current with shunt resistors is usually preferable. The shunt resistor approach provides a physically smaller, more accurate and temperature-stable measurement compared to a magnetic solution.

To evaluate and analyze a system's current information, the measurement must be digitized and sent to the system controller. There are many methods for measuring and converting the signal developed across the shunt resistor. The most common approach involves using an analog front end to convert the current-sense resistor's differential signal to a single-ended signal. This single-ended signal is then connected to an analog-to-digital converter (ADC) that is connected to a microcontroller. **Figure 1** illustrates the current-sensing signal chain.

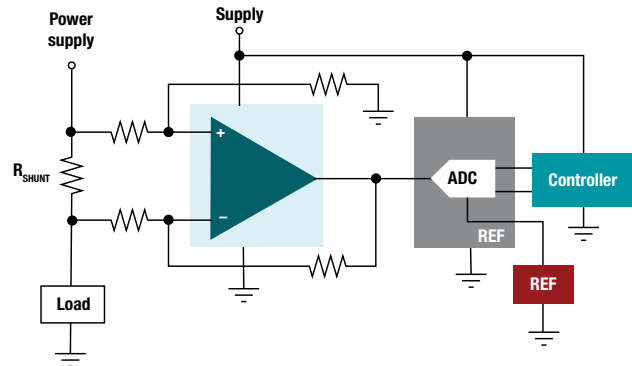


Figure 1: Current-sensing signal path

To optimize the current-sensing signal chain, you must appropriately select the shunt-resistor value and amplifier gain for the current range and full-scale input range of the ADC. Your selection of shunt resistor will be based on a compromise between measurement accuracy and power dissipation across the shunt resistor. A large-value resistor will develop a larger differential voltage as the current passes through. The measurement errors will be smaller due to the fixed amplifier offset voltage. However, the larger signal creates a larger power dissipation across the shunt resistor ($P = I^2 R$). A smaller shunt resistor develops a smaller voltage drop across the shunt resistor, reducing the power dissipation requirements and also increasing measurement errors, as the amplifier's fixed offset errors become a larger percentage of the signal.

Selecting the appropriate device that supports the desired amplifier gain will ensure that the amplifier's output signal will not exceed the ADC's full-scale input range at the full-scale input current level.

The [INA210](#) is a dedicated current-sense amplifier that integrates external gain-setting resistors, as shown in **Figure 2**. Bringing these gain resistors internal to the device enables increased matching and temperature drift stability compared to typical external gain-setting resistors. Space-saving quad flat no-lead (QFN) packages significantly reduce the board space requirements of an operational amplifier and external gain resistors. Current-sense amplifiers are

commonly available in multiple fixed-gain levels to better optimize pairing with shunt-resistor values based on the input current and ADC full-scale input ranges.

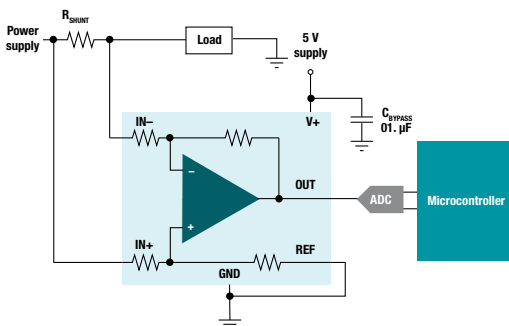


Figure 2: INA210 current-sense amplifier

Figure 1 showed the operational amplifier measuring the differential voltage developed across the shunt resistor and sending the amplified signal to the single-ended ADC. A fully differential input ADC can monitor the differential voltage directly across the shunt resistor. One drawback to using a typical ADC is the reduced input range. The signal developed across a shunt resistor will be small in order to limit the power-dissipation requirements of this component. Lower ADC resolutions will also impact small-signal measurement accuracy.

The ADC reference will be an additional error source that you must evaluate in this signal path. A typical ADC will feature an input range based on the converter's reference voltage. The actual reference voltage range varies from device to device, but is typically in the 2 V to 5 V range. The least significant bit (LSB) is based on the full-scale range and resolution of the converter. For example, a 16-bit converter with a full-scale input range of 2.5 V has an LSB value that's roughly 38 μ V.

The [INA226](#) is a specialized ADC designed specifically for bidirectional current-sensing applications. Unlike typical ADCs, this 16-bit converter features a full-scale input range of ± 80 mV, eliminating the need to amplify the input signal to maximize the ADC's full-scale input range. The INA226 is able to accurately measure small shunt voltages based on the device's maximum input offset voltage of 10 μ V and an LSB size of 2.5 μ V. The INA226 provides 15 times more resolution than the equivalent standard 16-bit

ADC with a full-scale input range of 2.5 V. The INA226 can directly monitor the voltage drop across the current-sense resistor, as shown in **Figure 3**.

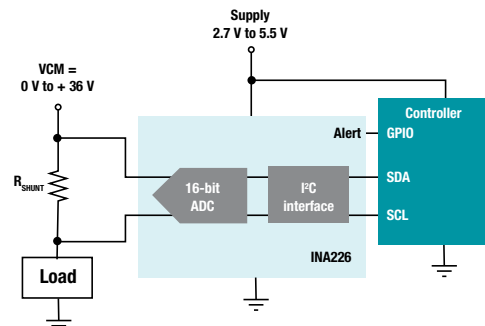


Figure 3: Digital current/power monitor

In addition to the ability to directly measure voltage developed across the shunt resistor as current passes through, the INA226 can also measure the common-mode voltage. The INA226 has an input multiplexer that enables the ADC input circuitry to switch between the differential shunt voltage measurement and the single-ended bus voltage measurement.

You can program the current-sense resistor value present in the system into a configuration register on the INA226. Based on this current-sense resistor value and the measured shunt voltage, on-chip calculations convert the shunt voltage back to current and can provide a direct readout of the system's corresponding power level. Performing these calculations on-chip reduces processor resources that would normally be required to convert this information.

Alternative device recommendations

For applications with higher performance requirements, the INA190 offers smaller input offsets and better drift and gain error performance.

For applications with lower performance requirements, the INA199 still offers the benefits of a dedicated current-sense amplifier.

For applications implementing overcurrent detection, the INA301 features an integrated comparator to allow for on-chip overcurrent detection as fast as 1 μ s.

For applications with lower performance requirements, the INA219 enables you to take advantage of a specialized current-sensing ADC.

Device	Optimized parameters	Performance trade-off
INA190	More accurate	Lower input offset voltage and gain error
INA199	Lower cost	Higher input offset voltage and gain error
INA301	Signal bandwidth, onboard comparator	Larger package: mini small outline package (MSOP)-8
INA219	Smaller package digital monitor, lower cost	Higher input offset voltage and gain error

Table 1: Alternative device recommendations

SBOA162C	"Measuring Current to Detect Out-of-Range Conditions"
SBOA165B	"Precision Current Measurements on High Voltage Power Supply Rails"
SBOA160B	"Low-Drift, Precision, In-Line Motor Current Measurements with Enhanced PWM Rejection"
SBOA161B	"Low-Drift, Low-Side Current Measurements for Three-Phase Systems"

Table 2: Related TI application notes

Integrating the current-sense resistor

Current is one of the most common signals used for evaluating and diagnosing the operational effectiveness of an electronic system. Because measuring this signal directly is very challenging, many types of sensors are instead used to measure the proportional effects that occur due to current flowing throughout the system.

The most common sensing element used for detecting current flowing in a system is a resistor. Placing a resistor, called a shunt, in series with the current path develops a differential voltage across the resistor as current passes through it.

One common signal-chain configuration for monitoring a current signal involves an analog front-end (AFE), an analog-to-digital converter (ADC) and a system controller, as shown in **Figure 1**. An AFE such as an operational amplifier or dedicated current-sense amplifier converts the small differential voltage developed across the shunt resistor to a larger output voltage that the ADC can digitize before sending the information to a controller. The system controller uses the current information to optimize the system's operational performance or reduce functionality in the event of an out-of-range condition to prevent damaging conditions from occurring.

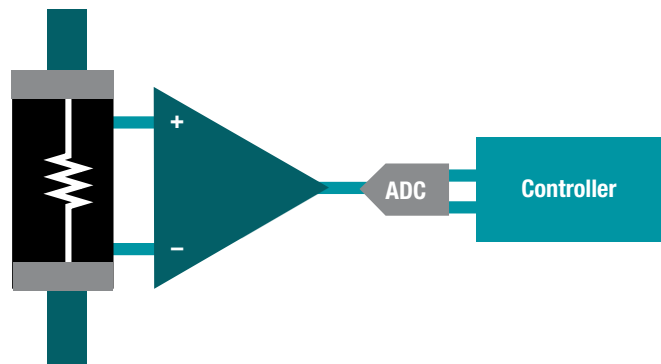


Figure 1: Current-sensing signal chain

Proper resistance-value selection is critical in optimizing the signal-chain path. The resistance value and corresponding voltage developed across the shunt results in a system power loss. To limit the power loss, it is best to minimize the shunt resistance. The resistor value is directly proportional to the signal developed and sent to the current-sense amplifier.

Amplifiers have fixed inherent errors associated with them (the input offset voltage, for example) that impact measurement accuracy. As the input signal increases, the influence of these internal errors on the total measurement accuracy decreases. When the input signal decreases, the corresponding measurement error is higher. This relationship between signal level and acceptable measurement accuracy provides generally lower limits for current-sense resistor selection.

The upper-limit value for the current-sense resistor should be limited based on the application's acceptable power loss for this component.

One benefit of using resistors for current measurement is the availability of accurate components that provide both high-precision and temperature-stable measurements. Precision current-sense amplifiers are available that feature measurement capabilities optimized for interfacing with very small signals to accommodate small-value resistors and low power losses.

There are two trends for resistors as the ohmic value decreases into the single-digit milliohm level and below. One trend for this segment of resistors is the reduced package availability and resistor value combinations. The other trend is the increased cost for precision and low-temperature coefficient components. Pairing a low-ohmic, low-temperature coefficient current-sense resistor with precision tolerance levels (~0.1%) results in solution costs in the several dollar range without including the cost associated with a precision amplifier.

A component such as the [INA250](#) (shown in **Figure 2**) or the INA253 helps reduce the challenges of selecting these increased accuracy, higher-cost resistors for applications needing precise and temperature-stable measurements. This device pairs a precision, zero-drift, voltage-output current-sense amplifier with a 2 mΩ integrated current-sense resistor with a 0.1% maximum tolerance and a temperature drift of 15 ppm/°C over the device's entire temperature range of -40°C to +125°C. This device can accommodate continuous currents flowing through the onboard resistor as high as 15 A. In addition to the integrated precision resistor inside this device, the INA250 and INA253 also addresses one of the most common issues associated with implementing a current-sensing solution. A low-ohmic shunt resistor reduces the current-sensing power dissipation. A challenge in accommodating this low resistance value is

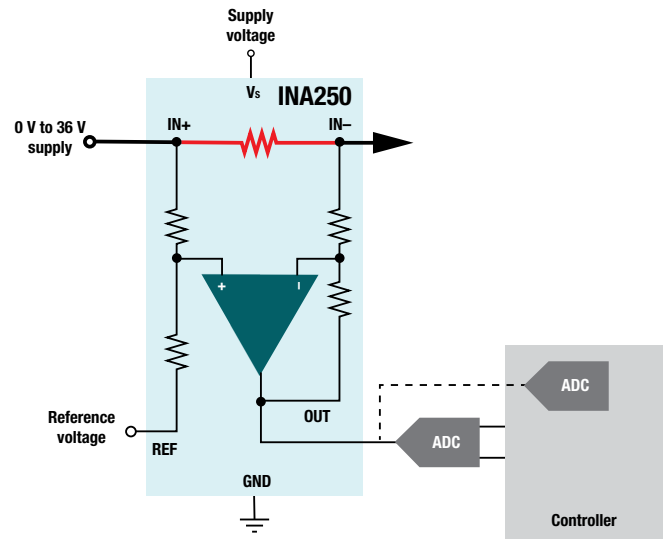


Figure 2: Integrating the current-sense resistor

the potential impact of parasitic resistance on the printed circuit board (PCB). Parasitic resistance in series with the shunt resistor can cause additional measurement errors as current flows through the resistance to create the shunt voltage. Poor layout techniques are the most common source for these measurement errors.

A Kelvin connection, also known as a four-terminal connection or a force-sense, is required to ensure that minimal additional resistance is present to alter the differential voltage developed between the amplifier's input pins. There are PCB layout techniques to reduce the effects of parasitic resistance; however, the INA250 or INA253 removes this concern.

As previously described, the typical current-sensing signal-chain path includes the current-sense resistor, the analog front end, ADC and system controller. The INA250 combines a shunt resistor and current-sense amplifier. The [INA260](#) combines a current-sense resistor, measurement front end and ADC into one device.

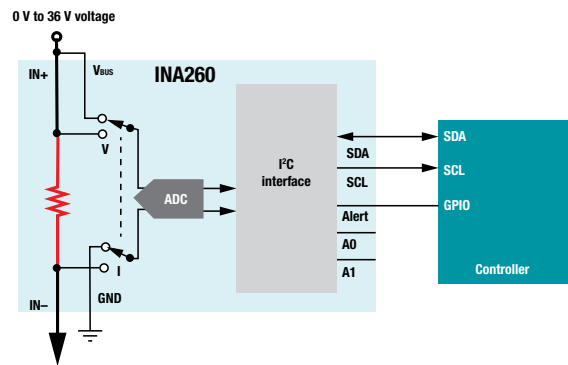


Figure 3: Integrated signal path

Pairing precision, low-drift current sensing with these precision current-sensing devices provides measurement solutions that would otherwise be challenging to accomplish using discrete amplifier and resistor combinations. There are few catalog current-sense resistors available capable of enabling a combination of precision and temperature-stable measurements, but achieving this level of accuracy in a solution size comparable to thin-shrink small outline package (TSSOP)-16 integrated solutions isn't possible.

Figure 3 shows the INA260, featuring the same precision, integrated sensing resistor, paired with a 16-bit precision ADC optimized for current-sensing applications. This combination provides even higher performance measurement capability than the INA250, resulting in a maximum measurement gain error of 0.5% over the entire temperature range and a maximum input offset current of 5 mA.

Alternative device recommendations

For lower-performance applications with higher current requirements than what integrated solutions support, use the INA210 stand-alone current-sense amplifier.

For applications requiring a stand-alone digital power monitor, use the INA226.

For applications implementing overcurrent detection, the INA301 features an integrated comparator for on-chip overcurrent detection as fast as 1μs.

Device	Optimized parameters	Performance trade-off
INA210	35μV input offset voltage, package: small-outline, quad flat no-lead (QFN)-10	No onboard current-sense resistor
INA226	10μV input offset voltage, package: mini small outline package (MSOP)-10	No onboard current-sense resistor
INA301	Signal bandwidth, onboard comparator	No onboard current-sense resistor

Table 1: Alternative device recommendations

SBOA162C	"Measuring Current to Detect Out-of-Range Conditions"
SBOA165B	"Precision Current Measurements on High Voltage Power Supply Rails"
SBOA167A	"Integrating the Current Sensing Signal Path"
SBOA169A	"Precision, Low-Side Current Measurement"

Table 2: Related TI application notes

Integrated, current-sensing analog-to-digital converter

The signal-chain path for measuring current is typically consistent from system to system. Whether current is measured in a computer, automobile or motor, nearly all equipment has common functional blocks.

The interface to a real-world element such as light, temperature (or current in this case) requires a sensor in order to convert the signal to a proportional value (voltage or current) that is more easily measurable. Several sensors use magnetic field sensing to detect the effects of current flow. These sensors can be very effective for detecting very large currents or when isolated measurements are required.

The most common sensor for measuring current is a current-sense or shunt resistor. Placing this component in series with the current being measured develops a proportional differential voltage as current passes through the resistor.

The remaining blocks in the signal path are selected based on how the system will use this measured current information. Several blocks are common to most applications, as shown in **Figure 1**. These blocks consist of an analog front end (AFE) to amplify a small signal from the sensor, an analog-to-digital converter (ADC) to digitize the amplified signal from the sensor and a processor that enables analysis of the sensor information so that the system can respond accordingly to the measured current level.

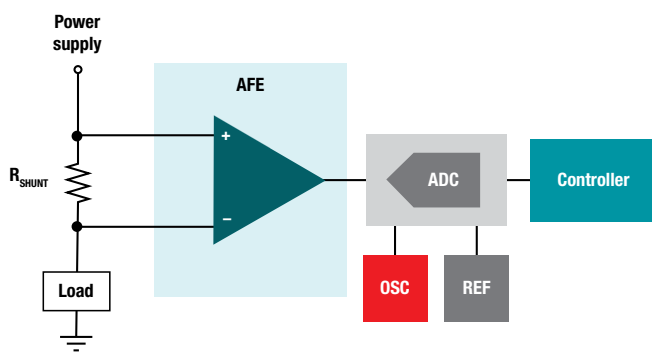


Figure 1: Current-sensing signal chain

One requirement for the AFE is to allow for a direct interface to the differential signal developed across the sense resistor. A single-ended output for the AFE simplifies the interface to the following ADC. Operational amplifiers in differential amplifier configurations are common for this functional requirement. Dedicated current-sense amplifiers such as the [INA210](#) feature integrated gain-setting components and are designed specifically for this type of application. The INA210 can accurately measure very small signals, reducing the power-dissipation requirements for the sensing resistor.

The next signal-chain block is the ADC, which is there to digitize the amplified sensor signal. This device can require additional external components (reference, oscillator) for more precise measurement capability. Like the AFE, there are various options available for the ADC block. Stand-alone converters with onboard references and oscillators are available, as are processors featuring onboard ADC channels.

Both integrated and discrete ADC blocks have their benefits as well as their limitations. One obvious advantage is that there are fewer components, since the ADC is integrated into the processor. Existing instruction sets for the onboard ADC channels further reduce the requirement for additional software to support a stand-alone ADC. However, silicon process nodes for digital controllers are frequently less optimized for precision analog, limiting the onboard converter's performance capability. Discrete analog-to-digital converters have an advantage of allowing device selection based on optimized performance attributes such as resolution, noise or conversion speed.

A variation in this signal chain is to use an ADC to measure directly across the current-sense resistor, eliminating the current-sense amplifier completely. A standard converter would have challenges in replacing the AFE and measuring the shunt voltage directly. One challenge is the large full-scale range of the ADC.

Without the amplification of the sense resistor's voltage drop, either the full range of the ADC cannot be fully

utilized or a larger voltage drop will be needed across the resistor. A larger voltage drop will result in larger power dissipation across the sensing resistor. There are ADCs available with modified input ranges designed for measuring smaller signals directly that can allow for the direct measurement of shunt voltages. An internal programmable gain amplifier (PGA) is typically integrated in these devices to leverage the full-scale range of the ADC.

One limitation that these small signal converters have is their limited common-mode input-voltage range. These ADCs have input-voltage ranges that are limited by their supply voltage (typically from 3 V to 5.5 V) based on the core processor voltage being supported. The [INA226](#), shown in **Figure 2**, is a current-sensing specific ADC that solves this common-mode limitation. This device features a 16-bit delta-sigma core and can monitor small differential shunt voltages on common-mode voltage rails as high as 36 V while being powered off a supply voltage that can range from 2.7 V to 5.5 V.

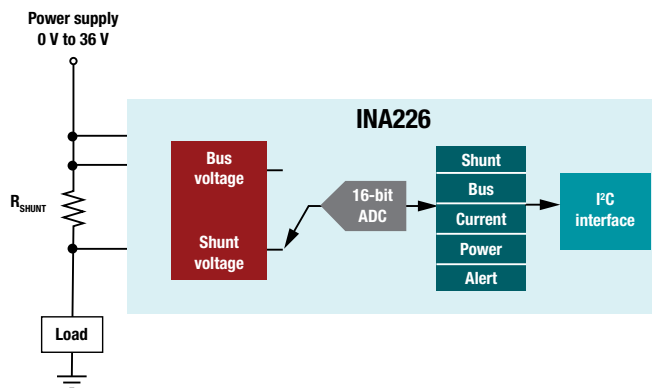


Figure 2: The INA226 precision current/voltage/power-sensing ADC

Similar to ADCs (with their modified small input range capability), the INA226 has a full-scale input range of about 80mV, enabling the device to measure directly across the current-sense resistor. The INA226 has the ability to very accurately resolve small current variations with a least significant bit (LSB) step size of 2.5 μ V and a maximum input offset voltage of 10 μ V. A 0.1 μ V/ $^{\circ}$ C offset drift ensures high measurement accuracy, with only an additional 12.5 μ V of offset induced at temperatures

as high as 125 $^{\circ}$ C. A 0.1% maximum gain error also enables the measurement accuracy to remain high at full-scale signal levels as well.

Although the INA226 can accurately measure small shunt voltages, this device has additional functionality useful for current-sensing applications. This device features an internal register that is user-programmable to the specific value of the current-sense resistor present on the printed circuit board (PCB). Knowing the value of the current-sense resistor enables the INA226 to directly convert the shunt voltage measured upon every conversion to the corresponding current value and stores this value to an additional output register.

The INA226 also features an internal multiplexer: the device can switch from a differential input measurement to a single-ended voltage configuration to enable direct measurement of the common-mode voltage. The voltage measurement, along with the previously measured shunt voltage and corresponding current calculation, gives the device the ability to compute power. The device stores this power calculation and provides this value along with the shunt voltage, current and common-mode voltage information to the processor over a two-wire serial bus.

In addition to the on-chip current and power calculations, the INA226 features a programmable alert register that compares each conversion value to a defined limit to determine if an out-of-range condition has occurred. This alert monitor is configurable to measure out-of-range conditions such as overcurrent, overvoltage or overpower. The device also includes programmable signal averaging to further improve measurement accuracy.

The INA226 is optimized to support precision current measurements. Additional features included in the device provide the capability of supporting the signal management and monitoring necessary and reducing the burden on the system processor.

Alternative device recommendations

For applications with lower performance requirements, the INA230 still leverages the benefits of a dedicated current-sensing analog-to-digital converter.

For additional precision-measurement capability where currents being measured are less than 15 A, the INA260 provides similar functionality to the INA226 while also featuring a precision 2 mΩ integrated current-sense resistor inside the package.

For applications requiring significantly higher common-mode voltage capability, the AMC1305 provides onboard isolation, supporting working voltages as high as 1.5 kVDC and handling peak transients as high as 7kV. For applications with lower AFE performance requirements, the INA210 still takes advantage of the benefits of a dedicated current-sense amplifier.

Device	Optimized parameters	Performance trade-off
INA210	35 μV input offset voltage, package: quad flat no-lead (QFN)-10	No onboard current-sense resistor
INA226	10 μV input offset voltage, package: mini small outline package (MSOP)-10	No onboard current-sense resistor
INA301	Signal bandwidth, onboard comparator	No onboard current-sense resistor

Table 1: Alternative device recommendations

SBOA162C	“Measuring Current to Detect Out-of-Range Conditions”
SBOA165B	“Precision Current Measurements on High Voltage Power Supply Rails”
SBOA167A	“Integrating the Current Sensing Signal Path”
SBOA170B	“Integrating the Current Sensing Resistor”

Table 2: Related TI application notes

Enabling Precision Current Sensing Designs with Non-Ratiometric Magnetic Current Sensors

Electronically controlled systems use local or remote sensor elements to monitor operating parameters for loop control, diagnostics, and system feedback. The quality and accuracy of this information is a key limit to system performance and control capability. In the past, where many electronics had poor control of sensor voltage supplies and references, ratiometry was used to reduce the errors due to parameter fluctuations. In modern systems, with tight control of references to signal chain elements such as analog to digital converters (ADCs), non-ratiometric sensors like the TMCS1100 magnetic current sensor enable improved noise immunity, precision, and design flexibility.

The linear transfer function of a current sensor is shown in Equation 1 with sensitivity (S) and zero current output voltage as gain and offset.

In a fully ratiometric device, both sensitivity and offset vary with the supply, so that full-scale input current always results in an output at either ground or supply, as illustrated by Figure 1.

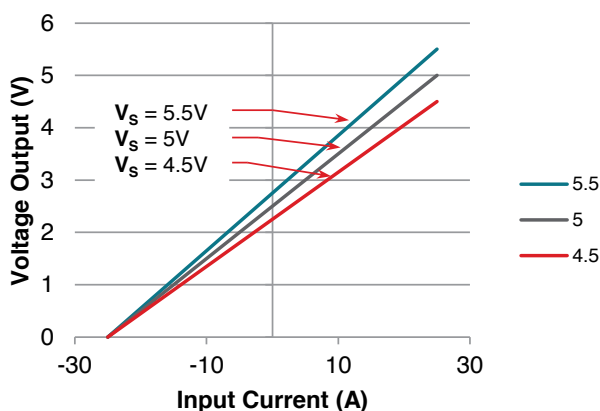


Figure 1. Fully Ratiometric Current Sensor Response

For a non-ratiometric current sensor, the change in voltage output for a given input current change has no dependence upon the supply, and the zero current output voltage is always a fixed voltage, as shown in Figure 2.

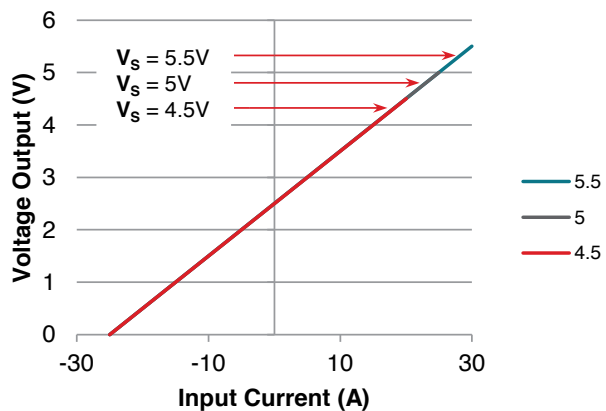


Figure 2. Non-Ratiometric Current Sensor Response

Ratiometry is effective in systems where a common sensor supply and ADC reference is expected to vary widely in operation, as shown in Figure 3. Ratiometry mitigates some of the error caused by a varying, ADC, full-scale reference by also scaling the sensor output range. However, ratiometry scaling is never perfect, and introduces some additional error to the system. It must be fine-tuned over a limited supply range for high accuracy, which reduces design flexibility, as sensor output range must identically match ADC input range. In addition, supply noise is directly injected into the output signal, which causes poor power supply rejection (PSR).

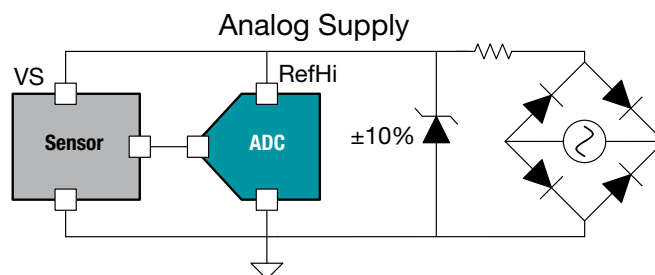


Figure 3. Ratiometric Sensor Architecture for Poorly Regulated Supplies

For systems where a stable ADC reference is available, either with a dedicated internal supply or an external reference, ratiometry only introduces additional error and noise. In these cases, such as in architectures shown in Figure 4, a current sensor with fixed sensitivity provides a superior solution. With a fixed sensitivity, the device has significant PSR, and can even have a different supply voltage than the ADC full scale. This is commonly the

case with integrated microcontroller ADCs. This also allows for optimization of fixed-sensitivity internal circuits, which provide higher total accuracy and lower drift.

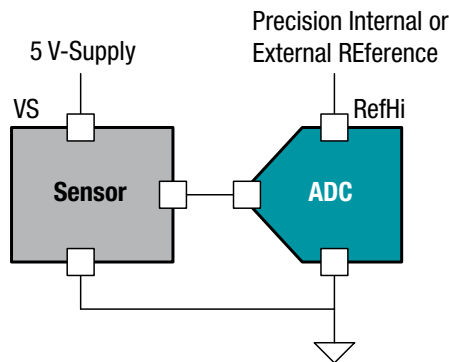


Figure 4. Non-Ratiometric Architecture for Precision Signal Chains

The [TMCS1100](#) and [TMCS1101](#) are precision, isolated magnetic current sensors with fixed sensitivity. The [TMCS1100](#) has an externally supplied reference pin that sets the zero current output voltage, which allows for both custom dynamic measurable ranges and a fully differential signal chain all the way to the ADC, as shown in Figure 5. This architecture, coupled with a precision, fixed-sensitivity signal chain, enables an industry-leading temperature stability with better than 1% accuracy from –40°C to 125°C.

Current sensors are often utilized in power systems where the sensor is often located near the power switching elements, far from the ADC and controller. This results in switching noise and transient events coupling directly into analog supplies and signals. A fixed-sensitivity sensor with an external reference allows the system to reject both of these noise paths. The improved PSR rejects noise injection through the analog supply and the external reference allows for pseudo- or fully-differential sensing, rejecting noise coupling into output signals. This results in lower system-level noise and improved dynamic range, as the differential measurement cancels any drift in the zero current output voltage.

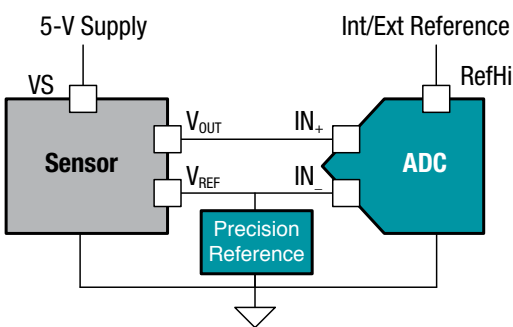


Figure 5. TMCS1100 Optimized Signal Chain

Design flexibility is greatly enhanced by this architecture, as the zero current output can be tailored to any use case condition. Bi-directional, uni-directional, and custom dynamic sensing ranges are achieved by appropriately selecting the reference voltage. Because there is no constraint between the sensor supply, reference, and ADC reference, the sensor output can cross voltage supply domains with no scaling required.

The [TMCS1101](#) has an internal resistor divider providing the reference, with variants of either 50% or 10%, of the supply for bi-directional and uni-directional current sensing respectively. It features a fixed sensitivity as well, and provides better than 1.5% accuracy across the full temperature range.

Document Type	Title
Application Note	Low-Drift, Precision, In-Line Isolated Magnetic Motor Current Measurements (SBOA351)
Application Note	Integrating the Current Sensing Path (SBOA167)

Table 1. Adjacent Tech Notes

Chapter 5: Wide VIN and isolated current measurement

Interfacing a differential-output (isolated) amplifier to a single-ended-input ADC

Whether you are sensing current in an industrial three-phase servo motor system, a battery-management system for an electric vehicle or a photovoltaic inverter, it is often necessary to include some sort of safety isolation scheme. Safety-related standards define the specific isolation requirements for the end equipment associated with a particular design. Various factors come into play when determining what level of safety insulation (basic, supplemental or reinforced) is required, depending on the type of equipment, the voltage levels involved and the environment in which the equipment will be installed.

TI offers a variety of isolated current-shunt amplifiers for voltage and current shunt sensing that meet either basic or reinforced insulation requirements. For applications requiring reinforced insulation, the output of the [AMC1301](#) is a fully differential signal centered around a common-mode voltage of 1.44 V that can be fed directly to a stand-alone analog-to-digital converter (ADC) as shown in **Figure 1**, or to the on-board ADC found in the MSP430™ and C2000™ microcontroller families.

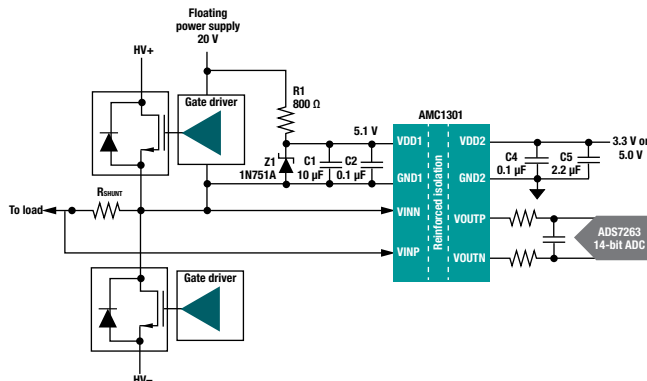


Figure 1: AMC1301 functional block diagram

Embedded ADCs

Both the MSP430 and C2000 processor families have embedded single-ended input ADCs – so the question becomes, “How do I get this differential signal into my

single-ended data converter?” The simplest way to achieve this is to use only one output of the AMC1301, leaving the second output floating. The downside to this solution is that only half of the output-voltage swing is available to the data converter, reducing the dynamic range of the measurement. The analog input range to the AMC1301 is ± 250 mV. With a fixed gain of 8.2, the VOUTN and VOUTP voltages are ± 1.025 V centered around the 1.44 V common-mode output, as shown in **Figure 2**. Differentially, the output voltage is ± 2.05 V.

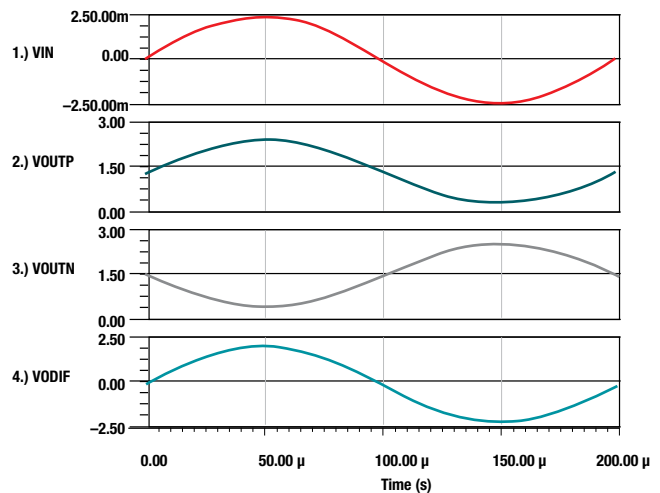


Figure 2: Differential output voltage

The addition of a differential to single-ended amplifier output stage, illustrated in **Figure 3**, enables the ADC to have access to the full output range of the AMC1301.

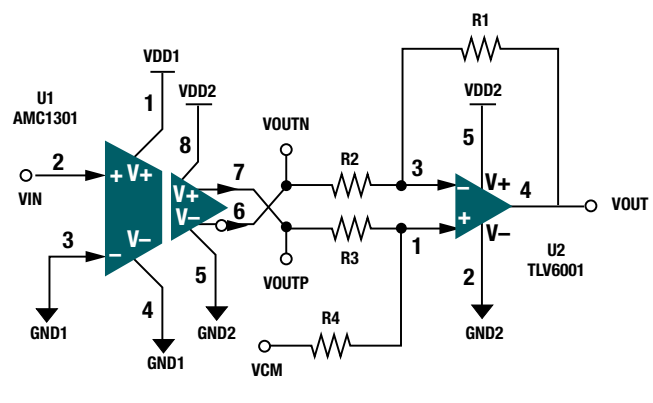


Figure 3: Differential to single-ended output

Assuming the application of a full-scale sine wave of $\pm 250\text{mV}$ at V_{IN} , the internal gain of the AMC1301 will provide 2.05 V peak-to-peak outputs at points V_{OUTP} and V_{OUTN} , which are 180° degrees out of phase. The difference between these signals, V_{ODIF} , is 4.1 V peak to peak. When $R_1 = R_4$ and $R_2 = R_3$, **Equation 1** shows the transfer function of the output stage:

$$V_{OUT} = V_{OUTP} \times \left(\frac{R_4}{R_3} \right) + V_{OUTN} \times \left(\frac{R_1}{R_2} \right) + V_{CM}$$

With equal-value resistors for R_1 through R_4 in **Equation 1** and V_{CM} set to 2.5 V , Equation 1 reduces to **Equation 2**:

$$V_{OUT} = (V_{OUTP} - V_{OUTN}) + V_{CM}$$

The plots in **Figure 4** show the input and output voltages of the AMC1301, along with the output voltage of the final differential to single-ended output stage. The differential voltage of $\pm 2.05\text{ V}$ transposes to a single-ended signal from 0.5 V to 4.5 V .

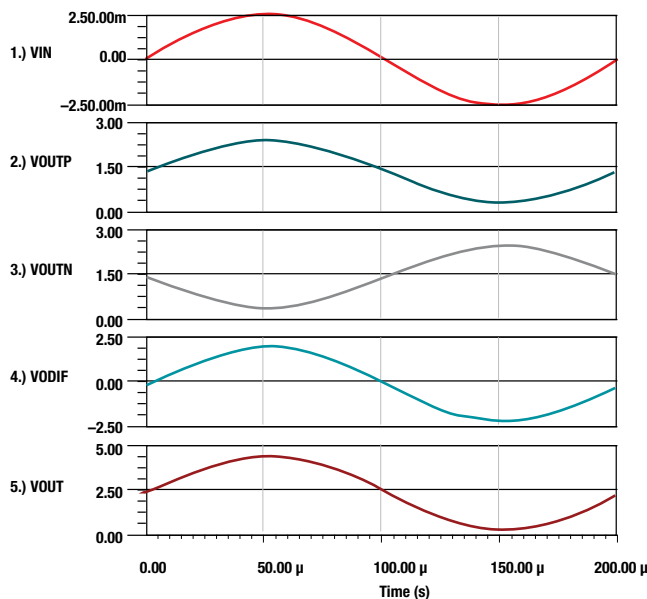


Figure 4: Single-ended output voltage

Depending on the input-voltage range of the ADC, you can incorporate gain or attenuation into the differential to single-ended stage to adjust the output swing. The output common-mode voltage is adjustable to fit the input needs of the ADC as well.

Design example

The embedded ADC found on most MSP430 devices has an input-voltage range of 0 V - 2.5 V when using the internal voltage reference. Using the V_{OUTP} from the AMC1301 would give the ADC an input signal ranging from 0.415 V to 2.465 V , well within the input range of the converter while using only half the input range of the AMC1301. As shown in **Figure 5**, by using a differential to single-ended amplifier configuration with a gain of 0.5 and a common-mode voltage of 1.25 V , the entire voltage range of the AMC1301 is applicable to the ADC.

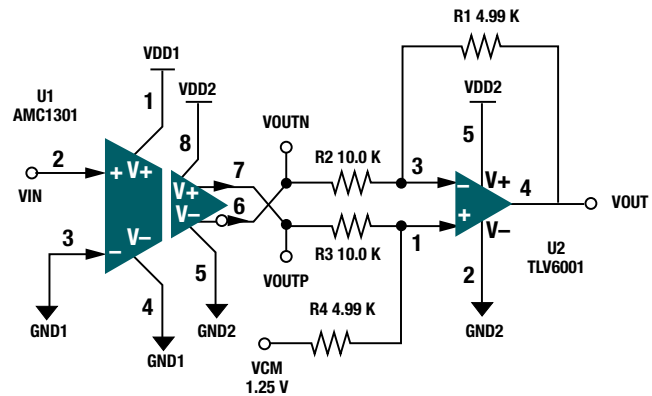


Figure 5: Scaled differential to single-ended output

While it is possible to use a single output of the AMC1301 to drive a single-ended ADC, adding a differential to single-ended operational-amplifier stage at the output ensures that the target application will have the largest possible dynamic range.

Alternative device recommendations

The AMC1100 or AMC1200 provide basic isolation with similar performance to the AMC1301 at a lower price point. For applications requiring a bipolar output option, the TLV170 is an excellent choice.

Device	Optimized parameters	Performance trade-off
AMC1100	Galvanic isolation up to 4,250 VPEAK	Lower transient immunity
AMC1200	Galvanic isolation up to 4,250 VPEAK	Basic isolation vs. reinforced
TLV170	Bipolar operation to ± 18 V	Higher input bias current

Table 1: Alternative device recommendations

SBOA161B	"Low-Drift, Low-Side Current Measurements for Three-Phase Systems"
SBOA165B	"Precision Current Measurements on High Voltage Power Supply Rails"

Table 2: Related TI application notes

Extending beyond the maximum common-mode range of discrete current-sense amplifiers

For high-side power-supply current-sensing needs, you must know the maximum voltage rating of the power supply. The maximum power-supply voltage will drive current-sense amplifier selection. The common-mode voltage of the current-sense amplifier should exceed the maximum voltage on the power supply. For example, if you are measuring current on the 48V power supply with a transient voltage not exceeding 96V, you'll need to design a current-sense amplifier with a maximum common-mode voltage supporting 96 V. For a 400 V supply, you'll need to choose a current-sense amplifier with a common-mode voltage supporting 400V.

The cost of high-voltage, high-side current sensing can be expensive if you need to achieve a goal of <1% accuracy. For common-mode voltages higher than 90 V, the selection of a current-sense amplifier is often limited to isolation technology, which can be expensive and bill-of-materials (BOM)-extensive. But it is possible to extend low-voltage common-mode current-sense amplifiers beyond their maximum ratings by adding a few inexpensive external components like resistors, diodes and p-channel metal-oxide semiconductor (PMOS) field-effect transistors (FETs).

Common-mode voltage divider using resistors

The simplest approach to monitoring high-voltage high-side current sensing is a design with a low-voltage current-sense amplifier with external input-voltage dividers. For example, if you select a 40 V common-mode voltage amplifier for an 80 V application, the 80 V

input common mode needs to be divided down to a 40 V common-mode voltage. You can divide this voltage using external resistor dividers, as shown in **Figure 1**.

This is a simple design approach, however, and the trade-offs are significant. The gain error and common-mode rejection ratio (CMRR) of the amplifier depend on the accuracy and the matching of the external input divider resistors. Apart from gain error and CMRR errors, the tolerance of the external resistors will contribute to an imbalance in the input voltage, causing additional output errors. This error does increase over temperature, depending on the drift specifications of the resistors. One technique to minimize output error is to use precision 0.1%-matched low-temperature-drift external resistor dividers.

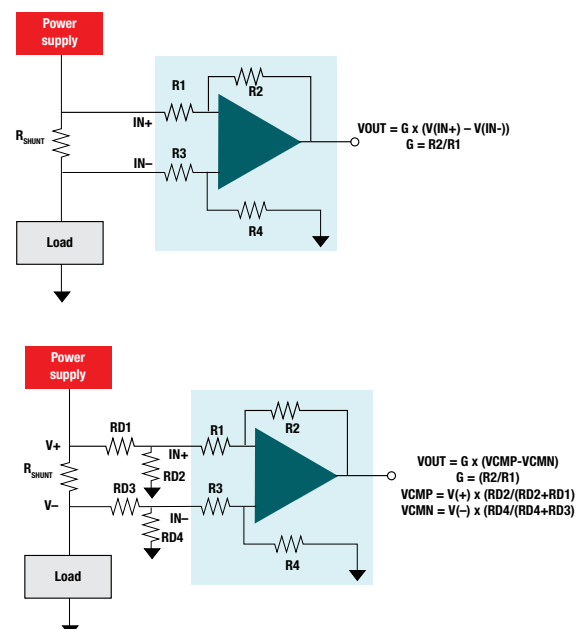


Figure 1: Extending the common-mode range using resistor dividers

Extending the common-mode range for current output amplifiers

Because voltage dividers have serious consequences with output error and performance degradation, another approach is to shift the ground reference of the current-output amplifier to the high-voltage common-mode node, as shown in **Figure 2**. **Figure 2** enables current sensing at higher voltages beyond the rated common-mode voltage of the INA168, which is 60V. You can extend this technique to any voltage beyond 60V by designing an appropriate PMOS FET (Q1).

In **Figure 2**, Zener diode DZ1 regulates the supply voltage in which the current shunt monitor operates, and this voltage floats relative to the supply voltage. DZ1 provides a sufficient operating voltage for the combination of IC1 and Q1 over the expected power-supply range (typically from 5.1 V to 56 V). Select R1 to set the bias current for DZ1 at some value greater than the maximum quiescent current of IC1.

The [INA168](#) shown in **Figure 2** is specified at 90 μ A maximum at 400 V. The bias current in DZ1 is approximately 1mA at 400 V, well in excess of IC1's maximum current (the bias current value selected limits dissipation in R1 to less than 0.1W). Connecting a p-channel metal-oxide semiconductor field-effect transistor (MOSFET), Q1, cascodes the output current of IC1 down to or below ground level. Transistor Q1's voltage rating should exceed the difference between the total supply and DZ1 by several volts because of the upward-voltage swing on Q1's source. Select RL, IC1's load resistor, as if IC1 were used alone. The cascode connection of Q1 enables the use of IC1 well in excess of its normal 60V rating. The example circuit shown in **Figure 2** was specifically designed to operate at 400 V.

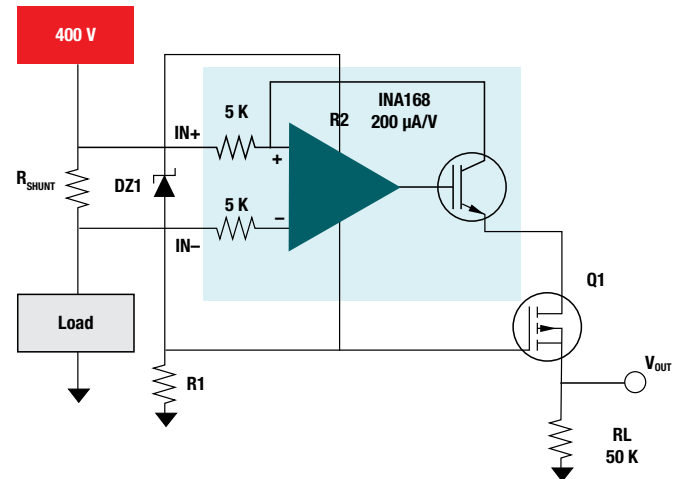


Figure 2: High-side DC current measurements for 400V systems

Extending the common-mode voltage range for power monitors

System optimization and power monitoring for high-voltage systems (40 V to 400 V), if implemented accurately, can result in improved system power management and efficiency. Knowing current, voltage and system power information can be beneficial in diagnosing faults or calculating the system's total power consumption. Monitoring faults and power optimization can prevent premature failures and significantly lower power savings by optimizing system shutdown and wake up.

Figure 3 illustrates a methodology by using the [INA226](#), a 36 V common-mode voltage power-monitoring device, for applications supporting 40 V-to-400 V systems.

Figure 2 shows is the precision, rail-to-rail OPA333 operational amplifier (op amp) used to mirror the sense voltage across the shunt resistor onto precision resistor R1. The OPA333 is floated up to 400 V using a 5.1 V Zener diode between its supply pins. The op amp drives the gate of the 600 V PFET in a current follower configuration. Choosing a low-leakage PFET enables accurate readings even at the low end of the measurement.

The voltage across R1 sets the drain current of the FET. By matching the resistor R2 in the drain of the FET to be equal to R1, the VSENSE voltage develops across R2 (VR2). Inputs of the INA226 current monitor connect across R2 for current sensing. Thus, the current monitor does not need the high-common-mode capability, as it will only see common-mode voltages around VSENSE, which are usually less than 100 mV.

The INA226 is a high-accuracy current/voltage/power monitor with an I2C interface. The INA226 can also sense bus voltages less than 36V. Since the bus voltage employed here is 400 V, a divider scales down the high-voltage bus to a voltage within the common-mode range of the INA226. With a ratio of 64, the bus voltage's least significant bit (LSB) can scale accordingly to obtain the actual bus voltage reading. In this case, you could use a modified LSB of 80 mV. Choosing precision resistors for the divider helps maintain the accuracy of the bus measurement.

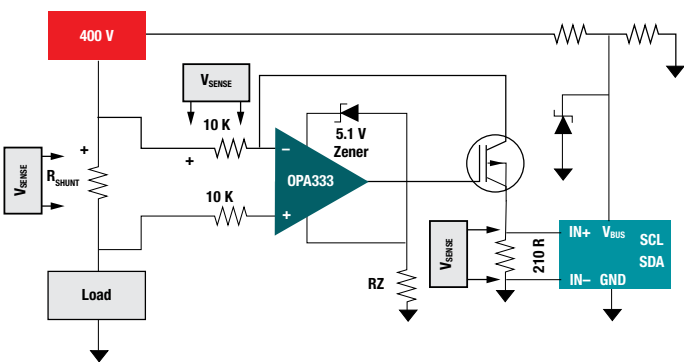


Figure 3: High-voltage power monitoring

Device	Optimized parameters	Performance trade-off
LMP8645HV	Bandwidth: 900 kHz, package: small-outline transistor (SOT)-23-6	Slew rate: 0.5 V/ μ S
INA220	Mini small-outline package (MSOP)-8, I2C interface, selectable I2C address	Gain error (1%), shunt offset voltage: 100 μ V
INA139	Package: SOT-23, bandwidth: 4,400kHz, cost	Offset voltage: 1 mV

Table 1: Alternative device recommendations

SBOA174A	“Current Sensing in an H-Bridge”
SBOA176A	“Switching Power Supply Current Measurements”
SBOA166B	“High-Side Drive, High-Side Solenoid Monitor with PWM Rejection”

Table 2: Related TI application notes

Low-Drift, Precision, In-Line Isolated Magnetic Motor Current Measurements

The demand for higher efficiency systems continues to increase, leading to direct pressure for improvement in motor operating efficiency and control. This focus applies to nearly all classes of electric motors, including those used in:

- White goods
- Industrial drives
- Automation
- Automotive applications

This is especially true in higher-power systems with elevated operating voltages. Operational characteristics of the motor fed back into the control algorithm are critical to ensure the motor is operating at peak efficiency and performance. Phase current is one of these critical diagnostic feedback elements used by the system controller to enable optimal motor performance.

Due to the continuity of the measurement signal and direct correlation to the phase currents, an ideal location to measure the motor current is directly in-line with each phase, as shown in **Figure 1**. Measuring current in other locations, such as the low-side of each phase, requires recombination and processing before meaningful data can be used by the control algorithm.

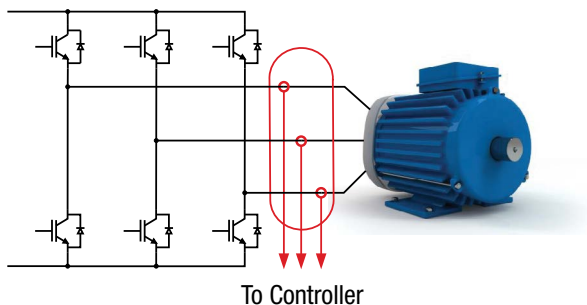


Figure 1. In-Line Current Sensing

The drive circuitry for the motor generates pulse width modulated (PWM) signals to control the operation of the motor. These modulated signals subject the measurement circuitry placed in-line with each motor

phase to large voltage transients that switch between the positive and negative power rails every cycle. An ideal current sensor has the ability to completely reject the common-mode voltage component of the measurement, and only measure the current of interest. In-package magnetic current sensors like the **TMCS1100** pass the phase current through a package leadframe, which creates an internal magnetic field. A galvanically isolated sensor then measures the magnetic field, providing a measurement of the current without any direct electrical connection between the sensor IC and the isolated phase current. By measuring only the magnetic field, the sensor provides isolation to high common-mode voltages, as well as excellent immunity to PWM switching transients. This results in excellent motor phase current measurements without unwanted disturbances at the sensor output due to large, PWM-driven input voltage steps. **Figure 2** illustrates an RC-filtered TMCS1100 output waveform, along with the motor phase voltage and current waveforms. Only minor PWM-coupling due to measurement parasitics are observable, and the TMCS1100 output tracks the motor phase current with no significant output transients due to the 300-V switching events.

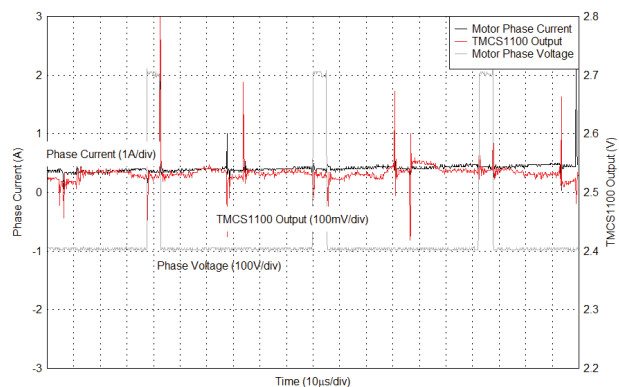


Figure 2. Motor Phase Current Measurement with High Transient Immunity

The unique characteristics of an in-package magnetic current sensor eliminate many of the challenges faced by alternative solutions to measuring motor phase currents. The inherent galvanic isolation provides capability to withstand high voltage, and the high transient immunity

of the output reduces output noise due to switching events. Current sensing implementations without this immunity require higher bandwidth in order to improve output glitch settling time; a magnetic sensor can use a lower-bandwidth signal chain without sacrificing transient immunity performance. In-package magnetic current sensors also provide a reduction in total solution cost and design complexity due to no requirement for external resistive shunts, passive filtering, or isolated power supplies relative to the high voltage input.

For applications where phase current measurements provide over-current protection or diagnostics, the high transient rejection of a magnetic current sensor prevents false overcurrent indications due to output glitches. In motor systems where closed loop motor control algorithms are used, precise phase current measurements are needed in order to optimize motor performance. Historically, Hall-based current sensors have suffered from large temperature, lifetime, and hysteresis errors that degrade motor efficiency, dynamic response, and cause non-ideal errors such as torque ripple. Common system-level calibration techniques can improve accuracy at room temperature, but accounting for temperature drift in parameters, such as sensitivity and offset, is challenging.

Magnetic current sensing products from Texas Instruments improve system-level performance by incorporating patented linearization techniques and zero-drift architectures that provide stable, precise current measurements across temperature. A high-precision sensor tightly controls phase-to-phase current measurement errors, maintaining accurate feedback control and delivering a seamless user experience.

The [TMCS1100](#) features less than 0.3% typical sensitivity error at room temperature, and less than 0.85% maximum sensitivity error across the entire temperature range from -40°C to 125°C . This stability across temperature, shown in **Figure 3**, provides excellent phase-to-phase matching by minimizing the temperature drift of the sensor.

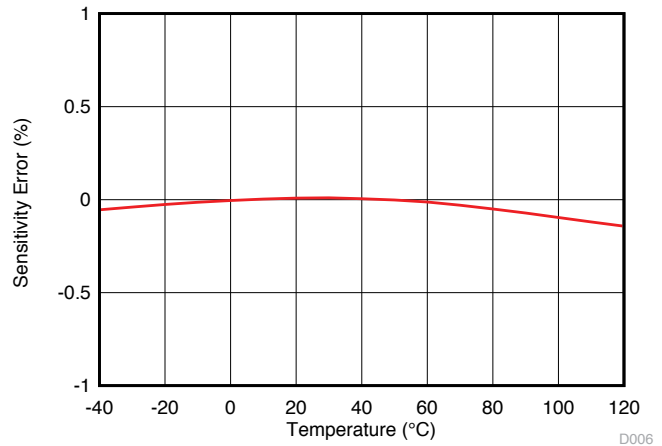


Figure 3. TMCS1100 Typical Sensitivity Error Across Temperature

In addition to high-sensitivity accuracy, the device has less than 2 mV of output offset drift, shown in **Figure 4**, which greatly improves measurement dynamic range, and allows for precise feedback control even at light loads.

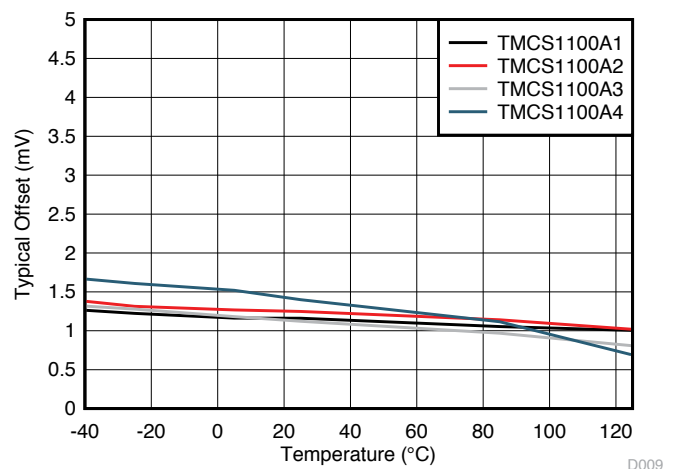


Figure 4. TMCS1100 Typical Output Offset Across Temperature

Combining high-sensitivity stability and a low offset results in an industry-leading isolated current sensing solution with $<1\%$ total error across the full temperature range of the device. A 600-V working voltage and 3 kV isolation barrier allows the device to fit into a wide array of high voltage systems. Combining measurement temperature stability, galvanic isolation, and transient PWM input rejection, the [TMCS1100](#) is an ideal choice for PWM-driven applications, such as motor phase current measurements, where accurate and reliable measurements are required for precisely controlled performance.

Device	Optimized Parameter	Performance Trade-Off
TMCS1101	Magnetic Current Sensor with Internal Reference	Lower precision, PSRR
AMC1300	Reinforced Isolation Shunt Amplifier	Solution size, complexity
INA240	Precision Shunt Amplifier with PWM Rejection	80V functional isolation
INA253	Precision Integrated-Shunt Amplifier with PWM Rejection	80V Functional isolation, size

Table 1. Alternate Device Recommendations

Lit #	Title
SBOA340	Ratiometric Versus Non-Ratiometric Magnetic Signal Chains
SBOA160	Low-Drift, Precision, In-Line Motor Current Measurements With PWM Rejection
SBOA161	Low-Drift, Low-Side Current Measurements for Three- Phase Systems
SBOA163	High-Side Motor Current Monitoring for Over-Current Protection

Table 2. Related TI TechNotes

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