White Paper
SBAA318A – February 2019 – Revised March 2019

Comparing shunt- and Hall-based current-sensing solutions in onboard chargers and DC/DC converters

Krunal Maniar

1 Introduction

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) offer higher fuel-efficiency and lower emissions compared to gasoline or diesel vehicles. To control energy flow and optimize efficiency in HEV/EV subsystems such as onboard chargers (OBC), traction inverters, DC/DC converters, and battery management systems (BMS), accurate current measurements at high common-mode voltages are essential. This document compares various isolated current-sensing methods based on several aspects such as performance, cost, and ease of implementation in OBCs and DC/DC converters.

1.1 Trademarks

All trademarks are the property of their respective owners.

2 Application Example: Onboard Charger (OBC)

An OBC converts grid AC voltage to an isolated DC output voltage for charging the high-voltage DC battery. The current measurements in OBCs typically range from 10 A to 60 A at AC input voltages from 85 V_{RMS} to 265 V_{RMS} and at DC output voltages from 200 V to 1000 V.

Figure 1 shows a simplified block diagram of a two-stage OBC. A PFC converter followed by an isolated DC/DC converter is the preferred topology for an OBC design. A non-isolated PFC boost converter ensures the rectified line current follows the rectified line voltage. This front-end PFC stage creates an intermediate DC bus with a relatively large ripple. An isolated DC/DC stage then provides galvanic isolation and a well-regulated, high-bandwidth output voltage with minimum current ripple flowing into the battery.

The microcontroller (MCU) or digital signal processor (DSP) receives feedback signals (voltage, current, temperature, and so forth) from the PFC and DC/DC stages and generates pulse width modulated (PWM) signals for controlling the field-effect transistors (FETs). Normally the MCU or DSP is referenced to a different ground domain (referred to as the *cold* side) and is isolated from the high voltage domain (referred to as the *hot* side). These feedback and control signals to and from the MCU or DSP must be isolated as well.

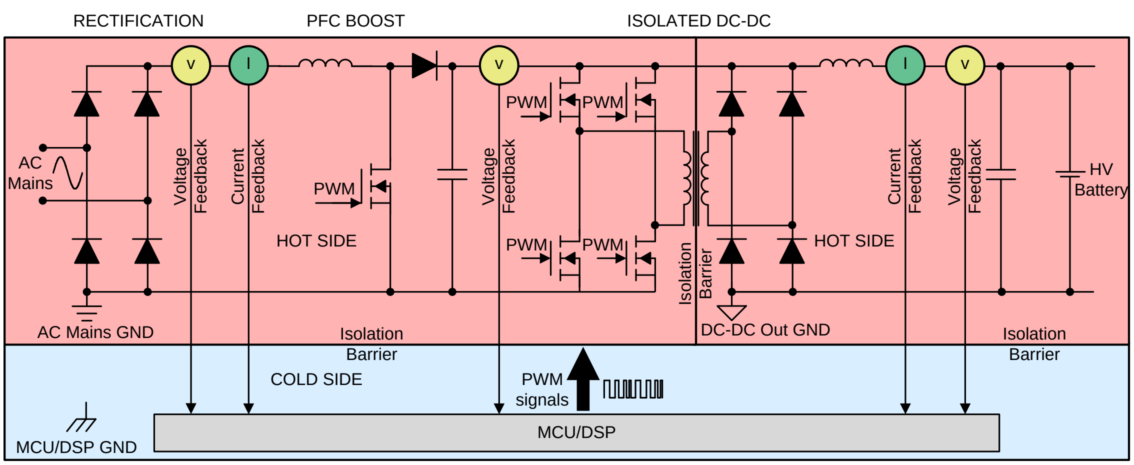

Figure 1. Block Diagram of a Two-Stage Onboard Charger (OBC)

2.1 Need for Accurate Current Measurements in OBC and DC/DC Converters

The general requirements of an OBC are high efficiency, low power, high reliability, high power density, low cost, small size, and light weight. The higher the efficiency of OBCs, the faster the high-voltage DC battery charging time. Faster charging times allow car manufacturers to design larger high-voltage battery packs that in turn offer longer driving ranges.

To optimize charging efficiency, the OBC is expected to have a power factor close to unity with minimal output ripple to charge the high-voltage battery. In addition, there are line harmonic current regulations that require high-power factor correction schemes to ensure that the harmonics and noise generated by the OBC do not enter the power grid. Failure to maintain a near unity power factor by the PFC stage compromises efficiency (for example, slower charging times and more heat dissipation) and also loads the grid.

As shown in Figure 1, an efficient AC to DC conversion is done by a PFC boost converter with a voltage control and a current control loop. The voltage control loop is used to regulate the PFC bus voltage to a preselected value and the current loop regulates the total average inductor current. The current control loop requires high measurement accuracy and bandwidth. The output of the current controller is fed to the digital PWM to generate a driving pulse for the boost switch. The control loop alters the duty cycle between 0% to 100% to control the input current. The input current of the PFC stage must be measured accurately to provide the current information for the current loop to ensure that the input current is in-phase to the line voltage. The voltage control loop requirements are not as demanding.

Current sensing also plays an important role in the isolated DC/DC stage of OBCs as well as standalone DC/DC converters. The current signals are used to minimize the load-droop voltages during transient loads and to control the feedback loop to provide a stable DC output voltage.

3 Different Methods for Isolated Current Sensing in OBC and DC/DC Converters

OBCs and DC/DC converters are subjected to up to 60 amperes of peak currents. The closed-loop hall modules are higher in cost compared to other solutions in OBCs and DC/DC converters and are therefore rarely used in these systems. Shunt-based methods using isolated amplifiers and isolated modulators, open-loop in-package, and open-loop module-based methods are all widely adopted in these systems.

- **Shunt-based solutions** offer higher accuracy and lower temperature drift than open-loop hall-based methods. Shunt resistors pair with isolated amplifiers (Figure 2) such as the AMC1302-Q1 or, for the highest-performing systems, an isolated delta-sigma modulator (Figure 3) such as the AMC1305M05-Q1.

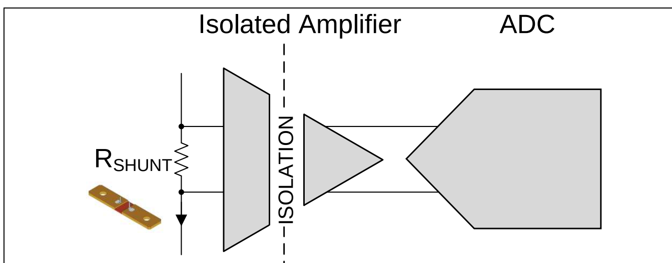

Figure 2. Isolated Amplifier

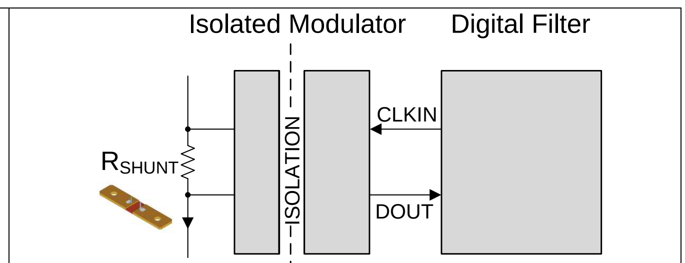

Figure 3. Isolated Modulator

- **Open-loop Hall sensors** use hall voltage directly to produce voltage output. There are two types of open-loop sensors, one that takes a module-based approach as shown in Figure 5, and another one that allows the current through the package (Figure 4) with the hall element and the semiconductor device in the same package. These sensors are easy to implement, but generally suffer from nonlinearity, gain, and offset errors. These parameters drift over temperature as well.

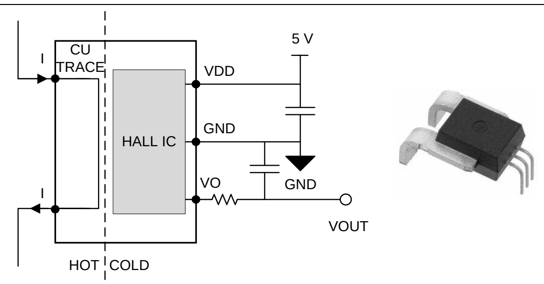

Figure 4. Open-Loop In-Package Hall Sensor

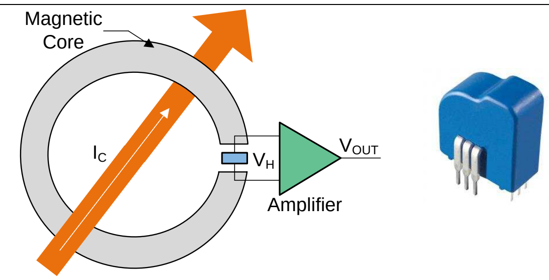

Figure 5. Open-Loop Hall Module

4 Comparing Shunt- and Hall-Based Solutions in OBCs and DC/DC Converters

With the advancements in EVs and HEVs, excellent current measurements are required to improve the efficiency of the entire HEV/EV drive train. Onboard chargers and DC/DC converters require very accurate current measurements across a wide dynamic range, typically from a few mAs to up to 60 As. In addition, these subsystems are subjected to hostile automotive environments (such as electrical noise, vibration, mechanical shock, temperature variations, ingress of contaminants, and so forth) and demand a robust, reliable, galvanic isolation, high speed, and yet low-cost solution with an extreme ease of integration and very low power consumption.

This section discusses some key considerations for designing an isolated current-sensing solution in OBCs and DC/DC converters.

4.1 Operating Temperature Range

Table 1 shows the operating temperature ranges for shunt- and hall-based solutions.

Table 1. Operating Temperature Range

PARAMETER	SHUNT-BASED		HALL-BASED
	SHUNTS	DEVICES	OPEN-LOOP
Operating ambient temperature range (typically)	Up to 170°C	–40°C to +125°C	–40°C to +105°C

- **Shunt-based:** The shunts used in OBCs and DC/DC converters typically have power ratings from 3 W to 7 W. These shunts are made of special metal alloys and can withstand temperatures as high as 170°C. There are shunts that go beyond the 170°C operating temperature range at the expense of size and cost. The semiconductor devices (isolated amplifiers, isolated modulators, operational amplifiers, and so forth) typically support up to 125°C ambient operation. In general, shunt-based solutions can withstand higher operating temperatures than hall-based solutions.
- **Hall-based:** Each ferrite material has a characteristic B-H curve. Beyond a certain temperature, referred to as the *Curie* temperature, the core permeability sharply disappears and the ferrite material is no longer magnetic. This effect limits the flux density inside the core material and the signal saturates when the temperature exceeds the curie temperature. Although most open-loop hall sensors have the operating temperature range limited to 105°C, few do support beyond 105°C ambient operation.

4.2 Isolation Voltage Ratings

Table 2 lists the operating temperature ranges for shunt- and hall-based solutions.

Table 2. Isolation Voltage Ratings

PARAMETER	SHUNT-BASED	OPEN-LOOP HALL-BASED	
	ISOLATED AMPLIFIER OR ISOLATED MODULATOR	IN-PACKAGE	MODULE
Isolation working and transient voltages	Very high (reinforced isolated devices) or medium (basic isolated devices)	Medium	Very high

- Texas Instruments' isolated amplifiers and isolated modulators use capacitive-coupled isolation barriers. The isolation voltages for reinforced isolated amplifiers and modulators are comparable to that of open-loop hall-based modules. The isolation voltages for basic isolated amplifiers and modulators are comparable to that of open-loop in-package hall solutions. TI recommends understanding the isolation requirements of the system before adopting either of these solutions.

4.3 Measurement Accuracy

Table 3 shows a comparison in terms of accuracy between the prevalent isolated current-sensing methods in OBCs and DC/DC converters.

Table 3. Measurement Accuracy

PARAMETER	SHUNT-BASED ISOLATED	OPEN-LOOP HALL-BASED	
	AMPLIFIER OR MODULATOR	MODULE	IN-PACKAGE
Electric offset error	Very low	High	High
Offset drift over temperature	Very low	High	High
Linearity error	Very low	High	High
Gain error drift over temperature	Very low	High	High
Magnetic susceptibility	Negligible	Very low	High
Overall achievable uncalibrated accuracy	< 2%	< 4%	< 5%
Overall achievable calibrated accuracy	< 1%	< 2%	< 3%

- **Shunt-based:** An isolated shunt-based current-sensing solution consists of a low ohmic-value shunt followed by an isolated amplifier such as the AMC1302-Q1 or an isolated modulator such as the AMC1305M05-Q1. With advancements in affordable high-precision, low-drift shunts and high-performance, low-drift isolated amplifiers and isolated modulators, a very high level of DC accuracy is attainable. The offset errors, linearity errors, gain errors, and their drifts over temperature are very low, allowing the system to achieve a very high level of calibrated and uncalibrated accuracy. Shunt-based solutions have negligible susceptibility to external magnetic fields.

  A shunt in the 500-µΩ to 1.0-mΩ range is ideal for OBC and DC/DC applications. These shunts dissipate approximately two to five watts of power under peak current conditions and cause negligible impact on overall efficiency. Because the peak current measurements are less than 60 As, the self-heating error contribution of the shunt to the overall system accuracy is normally negligible. However, to further enhance measurement accuracy, the drift of shunts over temperature because of self-heating and ambient temperature change can be calibrated by using a temperature sensor and correction algorithms. Shunts with 1% tolerance and a temperature coefficient resistance (TCR) of approximately 50 ppm/°C are relatively inexpensive at high volumes and are available in a small 2512- or 1210-size footprint.

Table 4 shows the worst-case error approximation of an isolated amplifier such as the AMC1302-Q1 and an isolated modulator such as the AMC1305M05-Q1.

Table 4. Worst-Case Error Over Temperature (–40°C to +125°C) at V_{IN} = +f_S (Full-Scale) = 50 mV

PARAMETER	MAX/TYP	ISOLATED AMPLIFIER AMC1302-Q1 DATA SHEET SPEC	ISOLATED AMPLIFIER AMC1302-Q1 RSS METHOD (1)	ISOLATED MODULATOR AMC1305M05-Q1 DATA SHEET SPEC	ISOLATED MODULATOR AMC1305M05-Q1 RSS METHOD	COMMENTS
Gain error	Max	0.3%	0.15 mV	0.3%	0.15 mV	
Gain drift	Max	50 ppm/°C	0.25 mV	40 ppm/°C	0.2 mV	Drift from 25°C to 125°C
Offset error	Max	100 µV	0.1 mV	50 µV	0.05 mV	
Offset drift	Max	0.8 µV/°C	0.08 mV	1.3 µV/°C	0.13 mV	Drift from 25°C to 125°C
INL	Max	0.03%	0.015 mV	5 LSB	0.04 mV	
INL drift	Typ	1 ppm/°C	0.03 mV	NA	NA	
Total error	Max	NA (2)	0.32 mV	NA	0.286 mV	Worst-case at +f_S
Total error after offset calibration	Max	NA	0.304 mV	NA	0.329 mV	Worst-case at +f_S
Total error	Max	NA	0.64%	NA	0.57%	Worst-case at +f_S
Total error after offset calibration	Max	NA	0.61%	NA	0.48%	Worst-case at +f_S

(1) RSS method = Root sum square method.
(2) NA = Not applicable.

Table 5 describes the approximate worst-case error of a shunt-based isolated amplifier and isolated modulator solution. For an isolated-amplifier-based solution, the approximation includes shunt tolerance, shunt drift, and error from the differential-to-single-ended stage as well. For an isolated-modulator-based solution, the measured analog signal undergoes only one analog-to-digital conversion. This solution eliminates the need for a differential-to-single-ended stage, and thereby reduces the number of components and solution size. The ADC used in an isolated-amplifier-based solution, which in many situations limits the maximum achievable sample resolution and accuracy, is not needed anymore as well. This isolated-modulator-based approach has improved signal noise performance, overall accuracy, and can achieve higher signal bandwidth and lower latency than an isolated-amplifier-based solution.

Table 5. Worst-Case System Error Over Temperature (–40°C to +125°C) at V_{IN} = +f_S (Full-Scale) = 50 mV

SPECIFICATION	AMC1302-Q1 SHUNT-BASED	AMC1305M05-Q1 SHUNT-BASED	COMMENTS
Worst-case error (max)	0.64%	0.57%	AMC1302-Q1 or AMC1305M05-Q1 error
Worst-case error after offset calibration (max)	0.61%	0.48%	AMC1302-Q1 or AMC1305M05-Q1 error
Shunt tolerance (1% max)	1.00%	1.00%	Tolerance assumed
Shunt drift (50 ppm/°C max)	0.50%	0.50%	Drift assumed
Differential-to-single-ended stage error (0.5% max)	0.50%	NA	Total resistor error assumed
Worst-case system error (–40°C to +125°C) (max)	1.38%	1.26%	Excludes ADC error for the AMC1302-Q1 solution
Worst-case system error (–40°C to +125°C) after offset calibration (max)	0.79%	0.69%	Excludes ADC error for the AMC1302-Q1 solution

- **Open-loop Hall sensors** solutions adopted in OBCs and DC/DC converters are less accurate than shunt-based solutions.

  Electric offset in open-loop hall sensors is significantly affected by temperature. The different expansion and contraction coefficients of the application-specific integrated circuit (ASIC) and the package affect the output signal. These temperature behaviors are unpredictable across ASIC to ASIC or from one production batch to another. Therefore, calibrating these offsets in production environments is very difficult.

  Magnetic offset error is induced by residual flux of the magnetic core in the transducer. This offset error depends on the previous core magnetization. Though impractical in many applications, magnetic offsets can be removed or minimized before making a measurement with the transducer by feeding a degauss cycle to demagnetize the transducer coil. Open-loop hall sensors are very susceptible to stray magnetic fields as well.

  Gain error or sensitivity error is generated by tolerances in the air gap between the hall sensor and the magnetic core brought out by the expansion and contraction of the core with temperature changes, mechanical stresses generated by the ASIC packaging, or by temperature and humidity changes. Similar to electric offset, these temperature behaviors are unpredictable from ASIC to ASIC or from one production batch to another. Therefore, calibrating these gain errors is very difficult.

  Linearity error is caused by the saturation of the magnetic core, and by the ASIC. To minimize linearity error, operate the transducer in the linear region of the response curve. The challenge with hall sensors is the change in the linearity curve over temperature. This variation makes hall sensors very vulnerable to linearity errors, thus making this error very difficult to calibrate in production environments.

  Table 6 shows the worst-case error approximation of an open-loop hall sensor solution.

Table 6. Worst-Case Error of an In-Package Open-Loop Hall Sensor

SPECIFICATION	MAX/TYP	DATA SHEET SPEC
Gain error	Max	1.5%
Electric offset error	Max	20 mV
Magnetic offset error	Max	0.6%
INL	Max	1%
Worst-case system error (–40°C to +25°C)	Max	±3.5%
Worst-case system error (25°C to 125°C)	Max	±2.4%
Worst-case system error (–40°C to +125°C)	Max	±4% (approximate)

4.4 *Latency, Bandwidth, and Noise Performance*

Table 7 shows a comparison in terms of bandwidth, latency and input-referred noise between the prevalent isolated current-sensing methods in OBCs and DC/DC converters.

Table 7. Latency, Bandwidth, and Noise Performance

PARAMETER	SHUNT-BASED		OPEN-LOOP HALL-BASED MODULE OR IN-PACKAGE
	ISOLATED AMPLIFIER	ISOLATED MODULATOR	
Signal bandwidth	up to 300 kHz further reduction with external filter	> 1 MHz achievable, trade-off between resolution and bandwidth	Up to 200 kHz
Signal latency	2 µs to 3 µs (fixed latency)	< 1 µs achievable, trade-off between resolution and latency	4 µs to 8 µs
Input-referred noise	Low	Very low, trade-off between resolution and latency or bandwidth	High

- **Shunt-based:** Shunt resistors are comprised of metal, ceramic compound, and carbon materials. As shown in Figure 6, these materials add additional parasitic inductance. Although shunt resistors are purely resistive at low frequencies, they pose bandwidth limitation at high frequency because of the parasitic inductance. The impact is more noticeable for low ohmic-value shunts.

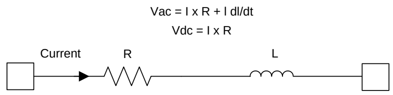

Figure 6. Shunt Effective Impedance

- Normally, the bandwidth and latency is limited by the isolated amplifier. With TI isolated-amplifier-based solutions, a latency less than 3 µs with a signal bandwidth up to 300 kHz is achievable. An external low-pass filter can be implemented to further reduce the signal bandwidth and optimize the noise performance.
- The shunts mainly suffer from thermal and current noise. Depending on the type of material, the shunts have different noise characteristics. Shunts are considerably less noisy and have better temperature stability compared to hall elements. TI's current-sensing isolated amplifiers offer a very low-noise programmable gain amplifier (PGA) in the front-end to improve noise performance. The improved noise performance in shunt-based solutions allows for accurate measurements across a wide dynamic range.
- Furthermore, isolated modulators provide a high-speed digital bitstream output that allows the user to create their own digital filters inside the MCU, DSP, or FPGA. The FPGA, MCU, and DSP can also have multiple digital filters running in parallel. One of the digital filters can be a high-performance digital filter that provides accurate feedback signals to control the bridge transistors. Another digital filter can be a low-latency digital filter for over-current detection. For more details, see the *Comparing isolated amplifiers and isolated modulators application report*.

- **Open-loop Hall sensors:** In open-loop hall sensors, the hall cell output voltage is amplified to output a copy of the measured current. However, any variation in the hall cell sensitivity, such as with temperature, gives an error. The electrical signal at the hall cell is very low, so the desire for a fast response time tends to give a noisy output because the signal bandwidth must be wide. Typically, the ASIC signal bandwidth must be larger than that of the current to be measured because, in order to overcome the offset and 1/f noise of the hall cell, its output must be modulated to a high frequency. This modulation is accomplished by biasing the cell successively in four orthogonal directions (*spinning* 1) and then demodulating after amplification. Because of the practical limitation associated with this spinning technique, open-loop hall sensors have limited bandwidth, typically less than 200 kHz and latency at approximately 5 µs to 10 µs. Some open-loop hall sensors avoid spinning and can support bandwidths up to 1 MHz, however these sensors suffer from poor accuracy and noise resolution.
- The hall element limits the noise of a hall sensor. The noise floor is derived from the thermal and shot noise values in hall elements. Open-loop hall sensors are inherently noisier, and when combined with their high sensitivity to temperature, are very vulnerable to noise. The noise of an open-loop hall sensor solution can easily be five to ten times than that of a shunt-based solution.

4.5 Manufacturability and Robustness

- **Shunt-based** solutions form a kelvin (4-wire, as shown in Figure 7) connection, resulting in more accurate current sensing. Because of this kelvin connection, there are fewer mechanical constraints in implementing the shunt and other active components on a printed circuit board (PCB) compared to a hall-based solution. The electric parameters are not very affected by vibrations or PCB flexing.

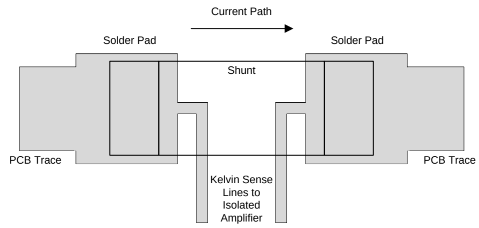

Figure 7. Kelvin (4-Wire) Connection

- **Open-loop hall sensors** require more attention during the installation process. These sensors have tight mechanical constraints and must be calibrated in production to meet the system accuracy requirements. Once assembled, these sensors are unaffected by vibrations or PCB flexing.

4.6 Solution Size and Component Flexibility

- **Shunt-based:** As shown in Figure 8, a typical shunt-based solution requires a shunt, an isolated amplifier or isolated modulator, and an isolated power-supply scheme for the high-voltage side. Depending on the end application, this isolated power-supply scheme can be used or shared with other active components onboard. Thus, there may not be a significant area or cost addition for generating the isolated power supply. For currents less than 100 A, shunts in the 2512- or 1210-size footprint, along with isolated amplifiers and an isolated power-supply circuit, provide a competitive solution in terms of size and better accuracy compared to open-loop hall sensors.

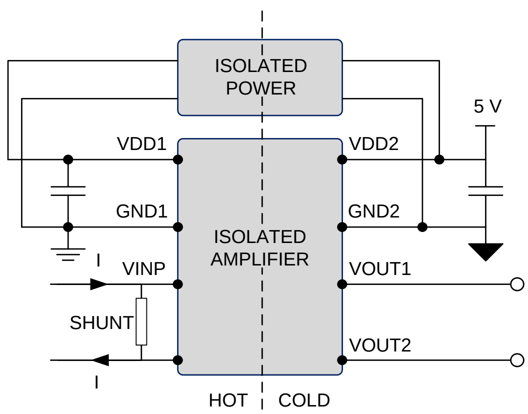

Figure 8. Shunt-Based Solution

- **Hall-based:** Because the currents in OBC and DC/DC applications are typically less than 60 As, in-package open-loop hall sensors are popular. These hall sensors have a thick copper conduction path and a monolithic semiconductor device in the same package. Alternatively, module-based open-loop hall sensors also provide a single-module approach but are slightly larger in size than the in-package ones. Open-loop hall-based solutions can offer very small form-factor sensors, however, the practicality of these in-package single-chip open-loop hall sensors diminishes with higher currents. For example, at currents greater than 100 As, the internal device temperature can rise up to 20°C, making designing in-package solutions challenging.

Open-loop hall sensors are inherently isolated, which allows a single-module or single-package monolithic approach. For measuring currents less than 100 As, use a careful selection of small-size shunts (2512 or 1210 size) and a double-sided PCB. Isolated-modulator-based solutions come very close in solution size and in general offer better accuracy than open-loop hall-based solutions.

4.7 Thermal Dissipation

- **Shunt-based:** The voltage drop across the inline shunt results in thermal dissipation and loss of power. This thermal dissipation results in loss of efficiency and increased temperature around the shunt. This increase in temperature, depending on the system design, can impact the overall accuracy of the system. However, with improvements in shunt technology, the shunts have become lighter, the ohmic values have decreased, and the accuracy and drift performance have improved. The use of low-ohmic value shunts results in reduced power loss and thermal dissipation. Additionally, Texas Instruments' isolated amplifiers and modulators are optimized for very small input voltage ranges (±50 mV and ±250 mV) and offer very low thermal drifts. These small ranges allow systems to have less thermal dissipation without compromising the overall measurement accuracy.
- **Hall-based:** Open-loop in-package hall-based sensors have an in-package conduction path, typically from 200 μΩ to 1.2 mΩ and dissipate almost the same amount of power as the shunt-based solution. The open-loop hall modules are contactless and do not dissipate power. This feature is one of the main advantages of open-loop hall-based modules.

4.8 Overall Solution Cost

The overall cost for either the shunt-based or hall-based solution involves a trade-off between temperature range, isolation voltage, accuracy, drift, bandwidth, noise, isolation voltage, and implementation.

For overall accuracy requirements greater than 5%, open-loop hall-based methods are cheaper than shunt-based solutions and have a stronger value proposition.

For overall accuracy requirements between 3% and 5%, hall-based and shunt-based methods are very competitive price-wise.

For overall accuracy requirements less than 3%, shunt-based methods have a stronger value proposition and are less expensive than open-loop hall-based methods. For meeting such high accuracy requirements (< 3%), hall-based methods become expensive and also require extensive calibration in production that add up to the overall cost.

5 Conclusion

Shunt-based and open-loop hall-based solutions are commonly used for isolated current sensing in OBC and DC/DC systems. With advancements in affordable high-precision shunts and high-performance isolated amplifiers and modulators, shunt-based solutions are good alternatives to traditional hall-based solutions.

Based on the solutions available in market, for relatively higher accuracy (< 3%) requirements, the benefits of isolated shunt-based methods outweigh the benefits of hall-based methods.

For accuracy requirements between 3% and 5%, shunt- and hall-based solutions compete in price and have their respective value propositions.

For relatively lower accuracy (> 5%) requirements, hall-based methods can be less expensive than shunt-based methods and have a stronger value proposition.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265