COMPARING PARAMETERS OF SHUNT-BASED AND HALL-BASED CURRENT SENSORS

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INTRODUCTION

Current sensing is a common requirement in many electrical systems and can be achieved with various solutions (see Figure 1).

Current sensing is most commonly performed using:

- Shunt-based solutions, which use a shunt resistor to convert a current into a low-voltage signal that is then amplified using a current-sense amplifier.
- Hall-based solutions, which use the Hall Effect, which is the presence of a voltage (V_{HALL}) across a biased Hall plate created by the magnetic field (B) of a current-carrying (I) wire (see Figure 2).

While various methods use the Hall effect to measure current—such as integrated conductor, core-based field sensing, or coreless field sensing—this application note focuses on Allegro integrated conductor Hall-effect current sensors.

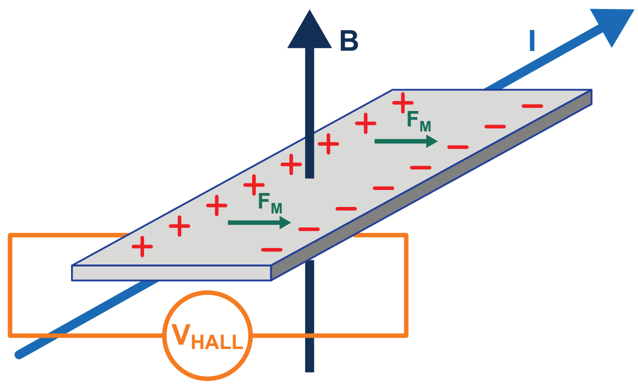

Figure 2: Hall-effect principle

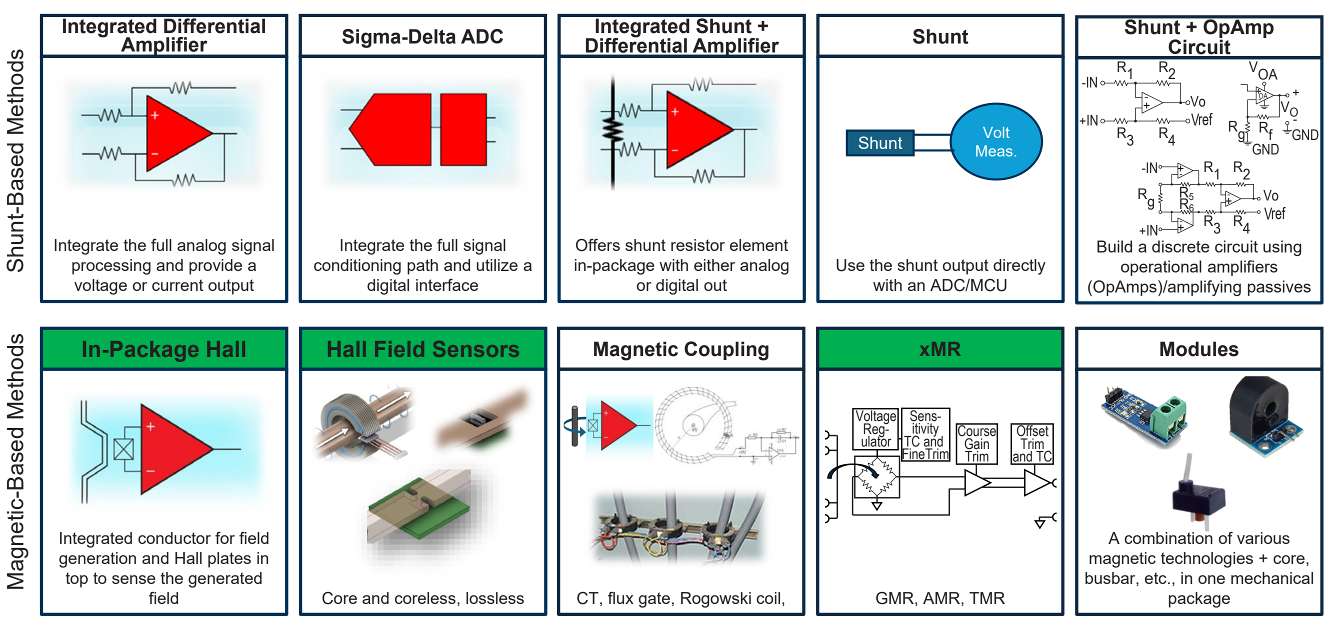

Figure 1: Common current-sensing solutions

These sensors route current directly through the package to concentrate the magnetic field and convert the level of current to a corresponding analog voltage output by means of the Hall effect and signal conditioning on the die (see Figure 3). The primary use cases for current sensors are:

- Current or power monitoring
- Control feedback
- Out-of-range detection (overcurrent protection)

Each use case and application have different requirements and parameters of interest. To enable an informed decision when selecting a current sensor for a specific application, this application note highlights many common parameters associated with current sensors and compares Shunt-based solutions to the Allegro integrated-conductor Hall-based solutions

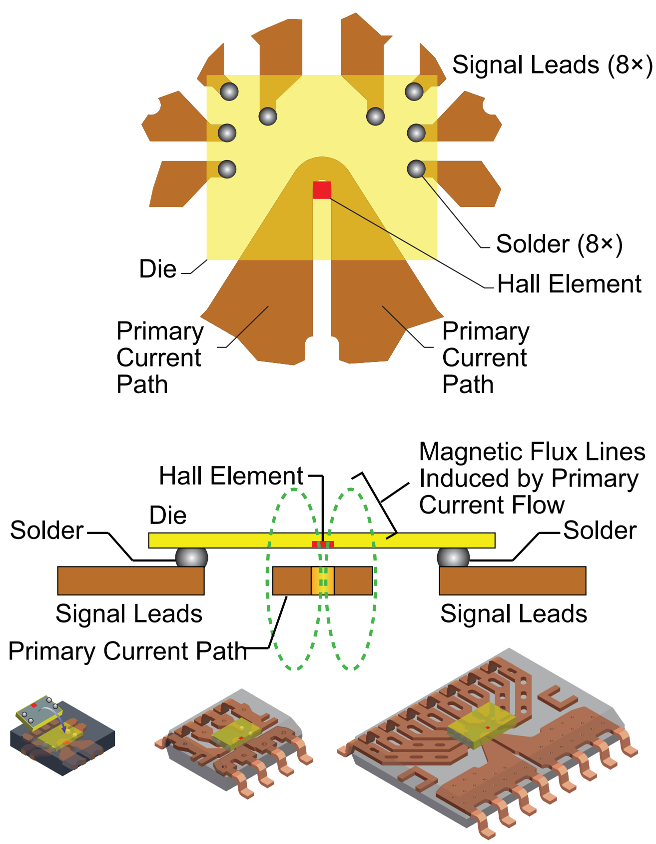

Figure 3: Internal conductor hall-based current sensors

WORKING VOLTAGE/ISOLATION

Shunt-Based Solutions

Traditional amplifiers do not specify isolation characteristics because they are not an isolating device. Instead, current-sense amplifiers specify a common-mode voltage, which is the average voltage between the two input pins and defines the maximum voltage limit that can be applied to the current-sense amplifier during typical operation (see Figure 4).

Common-mode voltage is limited by the fabrication process and the absolute-maximum voltage of the devices on the die being exposed. Compared to isolation characteristics, common-mode voltage is most similar to working voltage but with less stringent requirements and without isolation from input to output. Common-mode voltages of traditional current-sense amplifiers are usually less than 100 V, which limits Shunt-based solutions in high-side motor control or 120 – 240 V AC input applications. Isolated amplifiers avoid this by having an isolated supply on the input that transmits a digital signal through an isolation barrier that is converted back to an analog signal on the secondary side. These amplifiers are specified in a similar manner and have similar isolation characteristics to Hall-based solutions but require an additional, bulky supply. This increases the bill of materials (BOM) and overall footprint of the solution.

Hall-Based Solutions

One key benefit to Hall-based current sensors is inherent galvanic isolation. Because there is no electrical connection between the primary current path and the signal circuitry, high working voltages are available. While common-mode voltages are limited by electrical device capabilities, Hall-based isolation characteristics are a mechanical or package constraint. This isolation is tested across the isolation barrier of the device—or, in other words, a high-voltage potential is applied to the current-carrying pins and the signal pins are grounded (see Figure 4). Certifications require testing upon assembly and pins with a specified separation, referred to as creepage and clearance. In general, the isolation characteristics of Hall-based sensors are more rigorous because they are certified through UL standards.

Several isolation parameters or tests are included in the datasheets for Hall-based devices, such as:

- **Dielectric Surge Strength:** The amount of voltage that can be handled for a pulse of known rise time, width, and amplitude.
- **Dielectric Strength:** The amount of voltage and time that can be withstood before electrical breakdown occurs. This is tested for a set duration (typically 60 seconds) while measuring leakage current to ensure breakdown has not occurred.
- **Working Voltage:** The maximum voltage that can be continuously applied to the device. It usually has a specified value for DC, peak-to-peak, and RMS voltages.

Isolation characteristics are specific to the package of the device and range from 100 V DC working voltage, to greater than 1000 V DC working voltage with over 4 kV of dielectric strength.

Parameter	Shunt-based		Hall-based
	Standard	Isolated	
Working Voltage (Common-Mode Voltage)	<100 V DC	Up to > 1000 V DC	Up to > 1000 V DC
Dielectric Strength	–	Up to > 4 kV	Up to > 4 kV

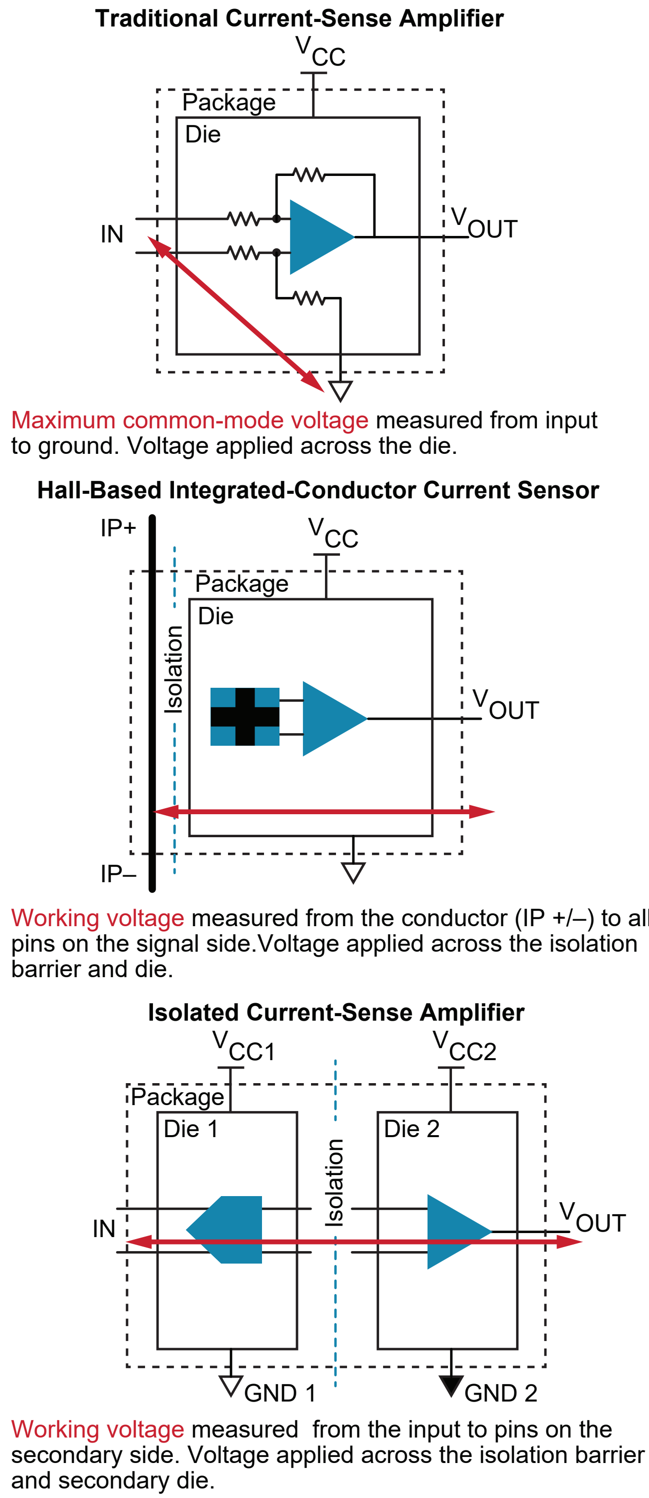

Figure 4: Working or common-mode voltage definitions for various methods

OPERATING TEMPERATURE RANGE

Shunt-based

Because shunt-based solutions have two components—shunt and amplifier—both operating temperatures must be considered. High-temperature and high-power shunts are available for up to several watts and with temperature ratings exceeding 150 °C; however, as power and temperature ratings increase, so do shunt size and cost. Most current-sense amplifiers are rated at 125 °C, although some amplifiers exist that are rated up to 150 °C.

Hall-based

Allegro offers a variety of operating temperature ranges depending on system requirements: –40 °C to 85 °C; –40 °C to 125 °C; and –40 °C to 150 °C. The main limitation of the operating-temperature range for these sensors is heat generated by the current flowing through the device. Thermal performance is further considered later in this application note.

Parameter	Shunt-based		Hall-based
	Shunt	Amplifier	
Operating Temperature Range	>150 °C	–40 °C to 125 °C	–40 °C up to 150 °C

ACCURACY

Shunt-based

When specified individually, amplifiers can achieve high gain and offset accuracy over temperature; however, these values in the datasheet do not equate to overall system accuracy. System accuracy must also include error caused by the shunt. Shunts have an error constraint (for example, ±1%) that can affect the amplifier output. Shunt resistances also increase as the material heats up, causing changes in temperature to affect the system output. At low frequencies, the impedance of the shunt is strictly composed of the resistive element; but, at higher frequencies, the parasitic inductance begins to increase the overall impedance, resulting in inaccurate measurements (see Figure 5).

$$V_{AC} = I \times R + dI/dt$$

$$V_{DC} = I \times R$$

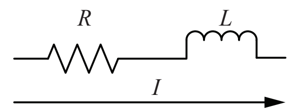

Figure 5: Effective impedance of shunt

High-precision (<1% error), low-temperature-drift (<50 ppm/°C) shunts are available at a higher price point, and filtering can be used to mitigate the error at higher frequencies caused by parasitic inductance at the cost of layout space surrounding the amplifier. In summary, shunt-based solutions can have very high accuracy if they are designed correctly using high-grade components, but not all shunt-based solutions are accurate at the system level.

Hall-based

Because the Hall effect uses a magnetic field instead of a shunt voltage to calculate current, any change in the conductor impedance by way of heating or parasitic inductance does not affect the current measurement. Instead, offset, gain, and temperature drift are caused by error in the Hall plates. Offset error can be high in Hall-based sensors, but Allegro employs a technique called chopper stabilization to remove key sources of the output drift induced by thermal and mechanical stresses. Offset error also plays less of a role at higher currents, making it minimal at full-scale current range. Offset may be calibrated out during software start up. Gain or sensitivity error is comparable with overall shunt-based solutions. Temperature drift in Hall-based solutions has a similar magnitude as shunt-based solutions but behaves in a nonlinear manner, which is why ppm/°C values are not included in datasheets for Hall sensors.

Parameter	Shunt-based	Hall-based
Offset Error	Low	Medium
Offset Drift Over Temperature	Low	Medium
Gain/Sensitivity Error	Low-Medium	Low-Medium
Gain/Sensitivity Drift Over Temperature	Medium (Linear)	Medium (Nonlinear)

BANDWIDTH/RESPONSE TIME

Shunt-based

Similar to accuracy parameters, the internal-bandwidth specified included in the datasheet of the current-sense amplifier does not necessarily equate to the system bandwidth. The parasitic inductance of the shunt reduces gain at higher frequencies and decreases response time. Shunt-based solutions can still achieve high bandwidth at frequencies exceeding 1 MHz by employing proper design considerations. Due to the communication required across the isolation barrier from the input to the output side of the device, isolated amplifiers are significantly slower in response time and bandwidth compared to nonisolated amplifiers. Isolated amplifier bandwidths typically reach a maximum of 300 kHz.

Hall-based

Because the parasitic inductance of the integrated conductor has no effect on the current measurement of a Hall-based sensor, the bandwidth is entirely dependent on the IC. While previous generations of Hall sensors exhibit bandwidth limitations at approximately 200 kHz, newer sensors can achieve 400 kHz; and, by removing chopper stabilization (sacrificing offset performance for speed), these sensors can achieve up to 1 MHz. Response times can be achieved down to 0.3 μs for these sensors.

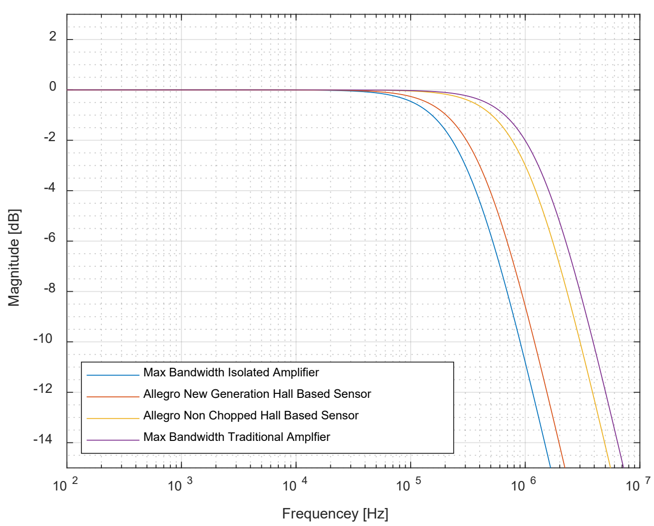

Figure 6: Bandwidth of various solutions

Parameter	Shunt-Based		Hall-Based
	Standard	Isolated	
Bandwidth	130 kHz to 1.3 MHz	300 kHz	120 kHz to 1 MHz
Typical Response Time	0.5 to 1 μs	2 to 3 μs	0.3 to 4 μs

CURRENT TRANSIENTS

Current sensing solutions must be able to handle and respond correctly to current transient events (dI/dt) in applications such as overcurrent detection.

Shunt-based

Parasitic inductance in the shunt resistor can cause a spike in output voltage during dI/dt events. These voltage spikes can lead to a false trip of the overcurrent detection or provide improper feedback.

Hall-based

Due to magnetic sensing, the inductance of the integrated conductor does not affect the current measurement. This results in smooth step responses in high dI/dt events, which—unlike shunt-based solutions—prevents false overcurrent flags, as shown in the lab data in Figure 7.

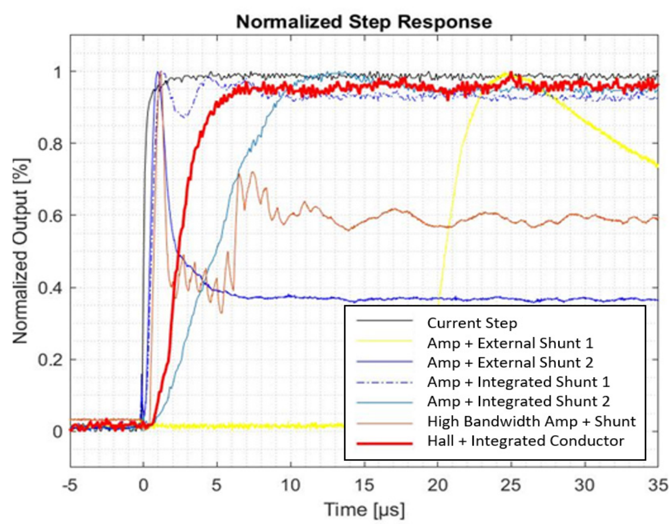

Figure 7: dI/dt current step response of various solutions

VOLTAGE TRANSIENTS

In switching applications, there can also be significant voltage transients (*dV/dt*), such as pulse-width modulation (PWM) signals for motor control or switch-mode power supplies. These voltage transients can pass into the signal chain and create inaccurate current measurements until the output has time to settle.

Shunt-based

Shunt-based solutions typically have a lower *dV/dt* capability with settling times greater than 1 µs and, in some cases, can be damaged from the voltage spike violating the common-mode voltage.

Hall-based

To prevent a noisy and unstable output during *dV/dt* events, techniques such as capacitive and conductive shielding are used to suppress the noisy signal, resulting in a magnetic-field signal that is void of electrical coupling between the leadframe and the sensor IC. Hall-based solutions typically have more-favorable *dV/dt* performance compared to shunt-based solutions, as evidenced by the lab data shown in Figure 8.

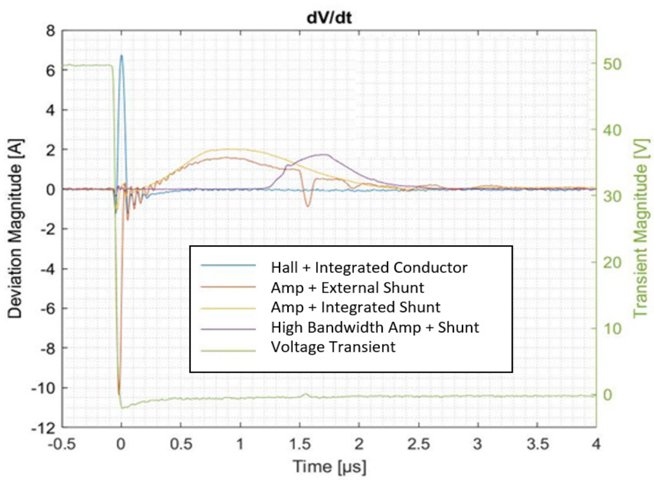

Figure 8: dV/dt voltage step response of various solutions

Parameter	Hall + Integrated Conductor	Amp + External Shunt	Amp + Integrated Shunt	High-Bandwidth Amp + External Shunt
Common-Mode *dv/dt* Error	1 A for 0.8 µs	1.8 A for 4.4 µs	1.25 A for 3 µs	2.45 A for 1.27 µs

NOISE/RESOLUTION

Shunt-based

Noise in current shunt resistors is comprised of two elements—thermal and current noise. Thermal noise is related to random electron movements at different temperatures and is independent of shunt material. Current noise is a result of imperfections in the conductor, which are minimal for metal alloy shunts and are higher in film shunts. Poorly joined solder joints can also increase noise in shunts. Current-sense amplifiers are generally low in noise, so shunt parameters dictate noise performance. Typically, shunt-based solutions have minimal noise and high resolution.

Hall-based

Noise is derived from the thermal and shot noise (current noise from the bias current in the Hall plate) observed in the Hall elements. The electrical signal produced by the Hall element is very small, which results in noise when amplified to the scale of the output voltage. In general, Hall-based solutions have higher noise levels than shunt-based solutions, but this is less important in high-current applications where the signal-to-noise ratio is much higher. Noise ultimately dictates the resolution of a sensor—the lower the noise, the better the resolution. Techniques such as output filtering and software averaging can also help to reduce the noise and improve the resolution of the Hall-based solution. Because Hall-based solutions sense current using magnetic properties, stray magnetic fields can result in noise or additional error. These magnetic fields can come from permanent magnets or from current-carrying traces or wires. To mitigate this magnetic noise or error, Allegro uses a dual-Hall-element approach on newer-generation devices. Dual-Hall devices route the conductor between two Hall elements that, through simple subtraction, can cancel out stray fields and mitigate magnetic-offset concerns.

Parameter	Shunt-Based	Hall-Based
Input-referred noise	Low	Medium

SOLUTION SIZE

Shunt-based

A primary driver of solution size for shunt-based solutions is the shunt resistor. As current levels increase, the footprint of the shunt resistor increases. High-current applications with low-resistance shunts can result in large or multiple shunts. For example, the typical size of 1 mΩ shunts is approximately 5 mm x 2.5 mm for those that can handle 0.5 W (22.5 A), and approximately 6.4 mm x 3.2 mm for those that can handle 1 W (45 A). Shunt-based solutions likely have an input filter to counteract the change in impedance of the shunt over frequency (as described in the Accuracy section), which occupies additional space. Even more layout space is required for isolated amplifiers. In addition to the required shunt and input filtering, isolated amplifiers require a dedicated isolated supply, which can consist of a transformer, transformer driver, and low-dropout (LDO) regulator.

Hall-based

Integrated-conductor Hall sensors offered by Allegro require no additional components or layout space aside from a bypass capacitor. This means that overall solution size for Hall-based sensors depends entirely on package size. Allegro offers package sizes down to 3 mm × 3 mm QFN packages for lower currents, and 10.3 mm × 10.3 mm packages for higher currents and reinforced isolation. In general, solution size is much smaller for Hall-based solutions, regardless of current and isolation requirements (see Figure 9).

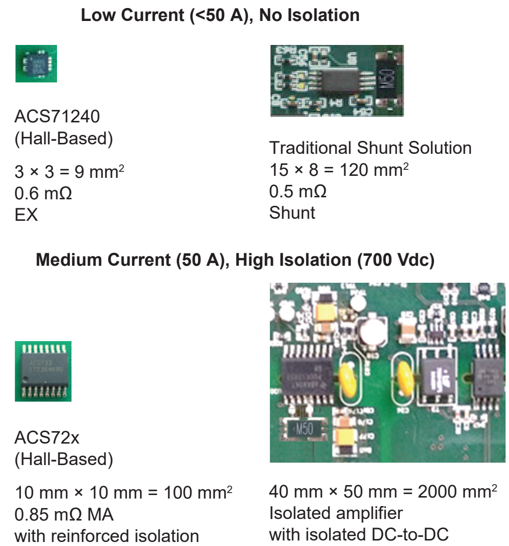

Figure 9: Layout of low-current (top) and medium-current (bottom) solutions

Parameter	Non-isolated Hall	Traditional Shunt with Amplifier	Isolated Hall	Isolated Amplifier with Shunt
Solution Size	3 mm × 3 mm	15 mm × 8 mm	10 mm × 10 mm	40 mm × 50 mm

DESIGN COMPLEXITY

Shunt-based

When designing with a shunt, power rating, accuracy, and resistance must be considered. It is important that the full-current range corresponds to the full-output range of the amplifier. To ensure this, shunt resistance multiplied by full-scale current should equal the differential-sense input range of the amplifier and gain should be such that the full-scale output matches the dynamic range of the analog to digital convertor (ADC). As mentioned in the Accuracy section, shunt inductance creates error at high frequency. To counteract this, a filter (pole) is needed to keep the total shunt and amplifier response reasonably flat, which also requires design work. Aside from component selection, proper layout can make or break a shunt-based solution. Poor layout can alter shunt resistance, which adds inaccuracies. Designing an isolated amplifier solution involves all the considerations already mentioned, with the addition of designing an isolated power supply.

Hall-based

Integrating the current path simplifies design, and using magnetic sensing eliminates the concern surrounding resistive and inductive inaccuracies in the current path. The sensor output is already configured for the full-scale input current and full-range output to a standard 5 V or 3.3 V ADC. The only additional design associated with Hall-based sensors is the option to add a resistor-conductor (RC) filter to the output to help mitigate potential noise, which is a simple calculation of desired output bandwidth.

Parameter	Shunt-based		Hall-based
	Standard	Isolated	
Design Complexity	High	Very High	Low

ROBUSTNESS

Shunt-based

Certain events can damage a current-sense amplifier during operation, such as a positive voltage spike, negative voltage spike, or current inrush. If the line being sensed has a spike in voltage, the maximum allowable common-mode voltage can be surpassed. A positive voltage spike can violate the allowable range, as can a negative spike a few volts below ground. Most current-sense amplifiers have a negative common-mode voltage range of approximately –2 V; this means they cannot handle substantial dips below ground or sense AC current. Additionally, an inrush of current outside the expected range can cause a voltage drop across the shunt resistor that exceeds the differential input range of the amplifier, also causing damage to the amplifier input.

Hall-based

Due to the isolation characteristics of Hall-based sensors, the high working voltages can apply to both positive or negative voltages. Voltage spikes can easily be handled because devices have a surge strength that often exceeds the working voltage of the senor by several kV. Additionally, when current flows through a device that is not within the sensing range, the output saturates and the device does not undergo damage.

Parameter	Shunt-based	Hall-based
Positive Voltage Spike	Damage is caused when voltage spikes exceed the common-mode range: approximately 100 V	Typically can handle several kV above the working voltage for 1 second
Negative Voltage Spike	Damage is caused when voltage spikes drop below the common-mode range: approximately –2 V	Typically can handle several kV above the working voltage for 1 second
Current Exceeds Sensing Range	Damage is caused when high current causes voltage drop across the shunt to exceed the differential input range of the amplifier	Output saturates with no damage to the device

LEVEL OF INTEGRATION AND OUT-OF-RANGE DETECTION

Shunt-based

Shunt and current-sense amplifier solutions are more discrete and lack some of the integration options that are available with Hall-based sensors. For instance, out-of-range detection (overcurrent detection) is an important use case for current sensors because it can prevent system damage by alerting the microcontroller unit (MCU) to remove power during a short-circuit event. This requires a digital flag to assert when a certain current threshold is met. A comparator is needed to compare the current-sense amplifier output to some fixed overcurrent threshold voltage. One comparator is needed for each threshold. This means that, if the application requires out-of-range detection in the positive and negative direction (or two positive thresholds), two comparator circuits are required. Additionally, the threshold to these comparator circuits is fixed with resistor ladders and cannot be changed easily.

Hall-based

As mentioned in the Design Complexity section, a primary integration benefit of the Hall sensor is the integrated conductor that removes the need to design for an external shunt and the associated difficulties. Another key integration benefit is the fault pin that is available on many Allegro integrated-conductor current sensors. This pin is a digital flag that alerts the MCU when an out-of-range threshold is met. The integrated fault pin eliminates the need for external comparators and functions in the positive and negative direction automatically for bidirectional parts. Depending on the device and applications, options are available to have two levels (warning and fault) and a pin to adjust the fault level dynamically. Isolation is also inherently integrated, so no additional work or design is required to achieve isolation with Hall-based sensors. Out-of-range detection configuration is compared in the block diagrams in Figure 10, which shows both: the Hall-based sensor with on-chip bidirectional fault output; and the discrete approach necessary for a shunt-based solution with bidirectional or unidirectional fault capabilities.

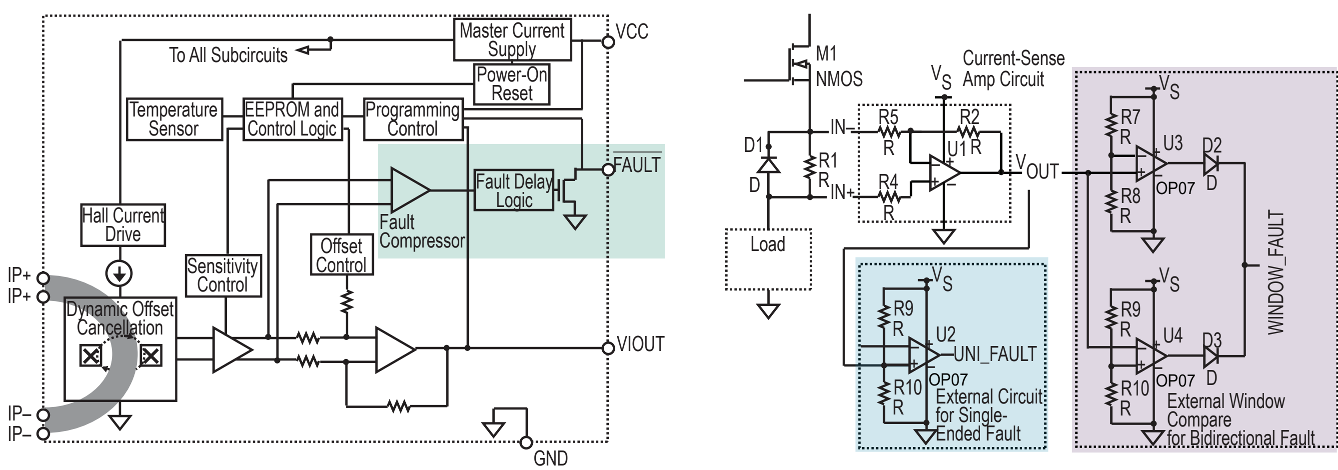

Figure 10: Block diagram comparison for out-of-range detection

Parameter	Shunt-based	Hall-based
Conductor	Requires shunt and input filtering	Integrated
Unidirectional Out-of-Range Detection	Requires comparator circuity	Integrated
Bidirectional Out-of-Range Detection	Requires two comparator circuits	Integrated (for bidirectional parts)
Isolation	Requires isolated supply (transformer, driver, LDO)	Inherent with no additional circuitry

POWER LOSS AND THERMAL DISSIPATION

Shunt-based

The voltage drop across the shunt dissipates heat and generates power loss. Because the bias voltage and current of an IC burns only a few mW, power loss and heat dissipation are dominated by the voltage drop across the shunt (or the integrated conductor in the case of a Hall sensor). Shunts typically range from 0.5 to 5 mΩ, and power loss grows exponentially with current ($P = I^2R$). Shunt thermal performance must also be considered to ensure the current does not push the temperature of the shunt beyond its operating temperature range.

Hall-based

The conductor generates a voltage drop and a power loss in a Hall-based solution in the same manner as a shunt solution. In general, conductor resistances in Hall-based solutions are less than their shunt counterparts and range from 0.1 to 1.2 mΩ. Higher-current devices have lower conductor resistances to further decrease power dissipation. Thermal management is also important in Hall-based solutions, but the packages are designed to maximize thermal performance in conjunction with proper layout techniques. Further information about thermal performance of various Allegro packages is available here. [1]

Parameter	Shunt-based	Hall-based
Power Dissipated at 25 A	0.625 to 3.125 W (1 to 5 mΩ shunt)	0.375 to 0.75 W (0.6 to 1.2 mΩ conductor)
Power Dissipated at 75 A	2.813 to 16.875 W (0.5 to 3 mΩ shunt)	0.56 to 1.52 W (0.1 to 0.27 mΩ conductor)

COST

Shunt-based solutions can be more cost-efficient/affordable but using a cheap shunt will increase engineering efforts and trouble shooting and decrease the chances of achieving desired accuracy and performance. When considering the price of a high-precision, low-drift shunt, the solution price is usually comparable to Hall-based sensors. Hall sensors have an especially good value proposition in applications where working voltage is greater than 100 V, such as in phase sensing for motor control and 120 to 240 V AC main sensing. Hall sensors are the less-expensive solution at high working voltages because it does not present costs associated with an isolated supply circuitry. A shunt-based solution requires an isolated amplifier—which is more expensive than a standard amplifier—and all the components associated with an isolated supply.

[1] https://www.allegromicro.com/-/media/files/application-notes/an296190-current-sensor-thermals.pdf?sc_lang=en

CONCLUSION

Shunt-plus-current-sense amplifiers are often thought of as the go-to current sensing technique simply due to a lack of awareness of other sensing techniques. Integrated Hall current sensors offer many benefits over shunt-based solutions, especially at high working voltages and high currents, or when performing out-of-range detection. Furthermore, Hall solutions are much smaller and can fit in small footprint PCBs where shunt-based solutions cannot. The only applications that gain a clear advantage from a shunt are ultra-low cost solutions that have very loose accuracy or performance requirements and low currents (<2 A) that require high precision and resolution; however, with the introduction of higher-resolution magnetic-sensing options, such as giant magnetoresistance (GMR) or tunnel magnetoresistance (TMR), shunt-based solutions are being challenged in the low-current sensing space.

Parameter	Shunt + Traditional Current-Sense Amplifier	Shunt + Isolated Current-Sense Amplifier	Allegro Integrated-Conductor Hall-Based Current Sensor
Working Voltage (Common-Mode Voltage)	<100 V DC	Up to >1000 V DC	Up to >1000 V DC
Max Temp	125 °C	125 °C	150 °C
Offset Error	Low	Low	Medium
Sensitivity Error	Low to Medium	Low to Medium	Low to Medium
Bandwidth	130 kHz to 1.3 MHz	300 kHz Max	120 kHz to 1 MHz
Noise	Low	Low	Medium
Solution Size	Medium to Large	Very Large	Small to Medium
Design Complexity	High	Very High	Low
Robustness	Can Sustain Damage from Voltage and Current Spikes	Can Sustain Damage from Current Spikes	Does Not Sustain Damage from Voltage and Current Spikes
Out of Range Detection	Requires External Circuitry	Requires External Circuitry	Integrated
Power Loss	Medium	Medium	Low
Cost	$-$$	$$	$$

Revision History

Number	Date	Description	Responsibility
–	February 5, 2024	Initial release	S. Locke

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