

Design considerations for isolated current sensing

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Industrial and automotive applications such as on-board chargers, string inverters and motor drives require some type of isolated current measurement to drive the feedback algorithm for the current control loop while protecting the digital circuitry from the high-voltage circuit performing a function.

Given their high performance, isolated amplifiers are excellent devices for transferring current-measurement data across the isolation barrier. However, selecting the correct isolated amplifier is not always a straightforward process. There are many decisions to consider when selecting an isolated amplifier, such as isolation specifications, how to power the high side and selection of the input voltage range. This article covers each of these decisions in detail to help select an isolated amplifier best suited to a specific system.

The first decision when selecting a device for isolated current measurement is to determine the level of isolation required. There are two levels of isolation, basic and reinforced. System architecture and end-equipment standards such as International Electrotechnical Commission (IEC) 61800 for motor drives and IEC 60601 for medical equipment will specify the required isolation level.

Here are the main specifications that quantify the performance of the isolation barrier:

- The isolation working voltage is the maximum voltage defined in the root-mean-square voltage that the isolated amplifier can handle continuously throughout its operating life.
- Common-mode transient immunity describes the maximum rate of change in ground potential difference that the isolated amplifier can withstand without errors.
- The isolation transient overvoltage is the voltage defined in the peak-to-peak voltage that the isolated amplifier can tolerate for 60 s.
- The surge rating (impulse voltage rating) according to IEC 60065 is the 1.2-/50- μ s voltage magnitude that the isolated amplifier can tolerate without failure.

Some end-equipment manufacturers have their products certified by third parties to verify that they meet isolation specifications. Isolated amplifiers are not measured to these specifications themselves, since they are components inside end equipment, and end-equipment standards apply only indirectly to them. Instead, components are measured against device-level certifications such as Deutsches Institut für Normung e.V. (DIN) Verband Deutscher Elektrotechniker (VDE) V 0884-11 and Underwriters Laboratories (UL) 1577. As stated in the IEC standards, devices complying with

component-level standards that have equivalent requirements do not require separate evaluation. This applies to Comité International Spécial des Perturbations Radio (CISPR) radiated emissions electromagnetic interference (EMI) standards as well. See Reference 1 for radiated emissions performance for isolated amplifiers from Texas Instruments (TI).

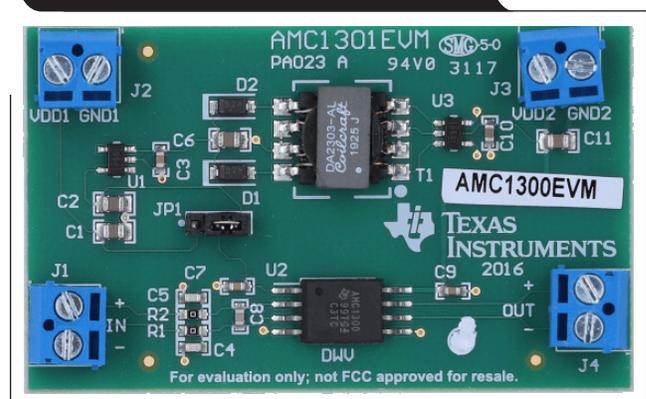
For the best performance, the layout and application practices shown in the device data sheet are recommended; Reference 2 lists the TI isolated amplifier device-level certifications.

The next decision when selecting an isolated amplifier is how to power it on the high side of the isolation barrier. When designing this portion of the circuit, remember that the high-side supply voltage must float with the common-mode input voltage of the current being measured. This means that for multiple-phase current measurements, each phase requires one isolated amplifier with its own high-side power supply. Incorrectly designing the high-side power-supply circuit can lead to exceeding the absolute maximum analog input-voltage ratings, which can cause permanent damage to the device.

There are three main design options to power the high side of an isolated amplifier.

The first design option is to design a discrete isolated transformer circuit that can supply voltage to the high side of the isolated amplifier from the low side. This method will require selecting an isolated transformer, a transformer driver such as TI's SN6501 and a low-dropout regulator such as TI's TLV704. Although easy to design, this approach requires a large board area and several components. Figure 1 illustrates an example implementation on the top portion of the AMC1300 evaluation module (EVM).^[3]

Figure 1. The AMC1300 EVM with an isolated transformer



The second design option, shown in Figure 2, uses the floating high-side gate driver supply (typically 15 V) and a shunt regulator such as a Zener diode to regulate the voltage down to 5 V. Examples of this design are in the device data sheets, such as the AMC1300B-Q1 reinforced isolated amplifier. While this design option is economical and effective, layout restrictions and parasitic impedances between the gate-driver-supply ground reference and the amplifier ground reference can lead to common-mode input voltage violations and transient errors.

The third and simplest design option, shown in Figure 3, uses a device with an integrated DC/DC converter. Isolated amplifiers with integrated DC/DC converters such as TI's AMC3302 greatly reduce solution size and complexity, lower system costs, provide excellent conversion efficiency, and enable flexible placement of the shunt resistor.^[4]

The last decision when selecting an isolation amplifier is to select the input voltage range of the device. Most isolated amplifiers optimized for current sensing have options for either a $\pm 50\text{-mV}$ or $\pm 250\text{-mV}$ linear-input

Figure 2. The AMC1300B-Q1 and a floating power supply

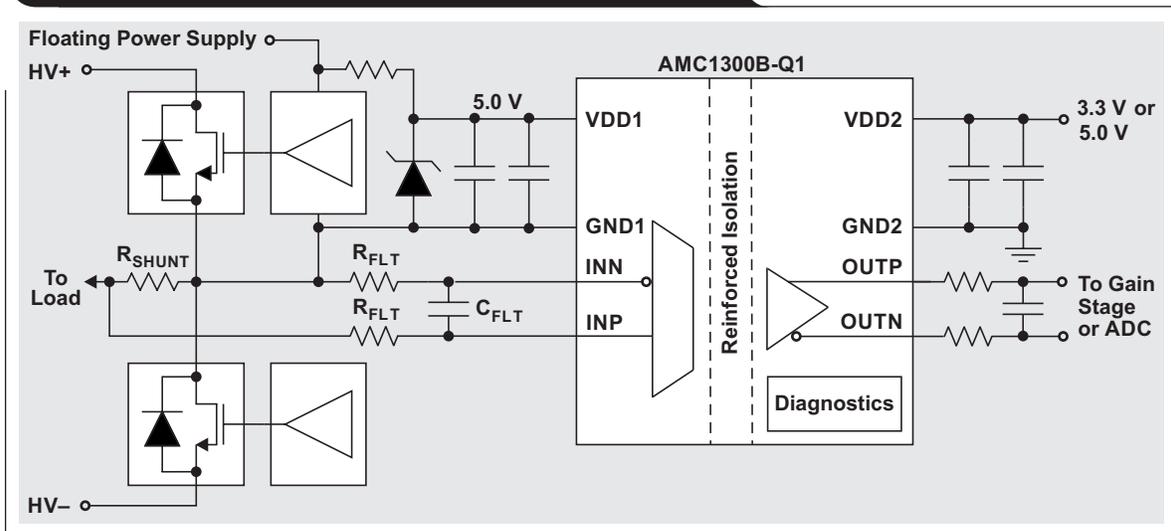
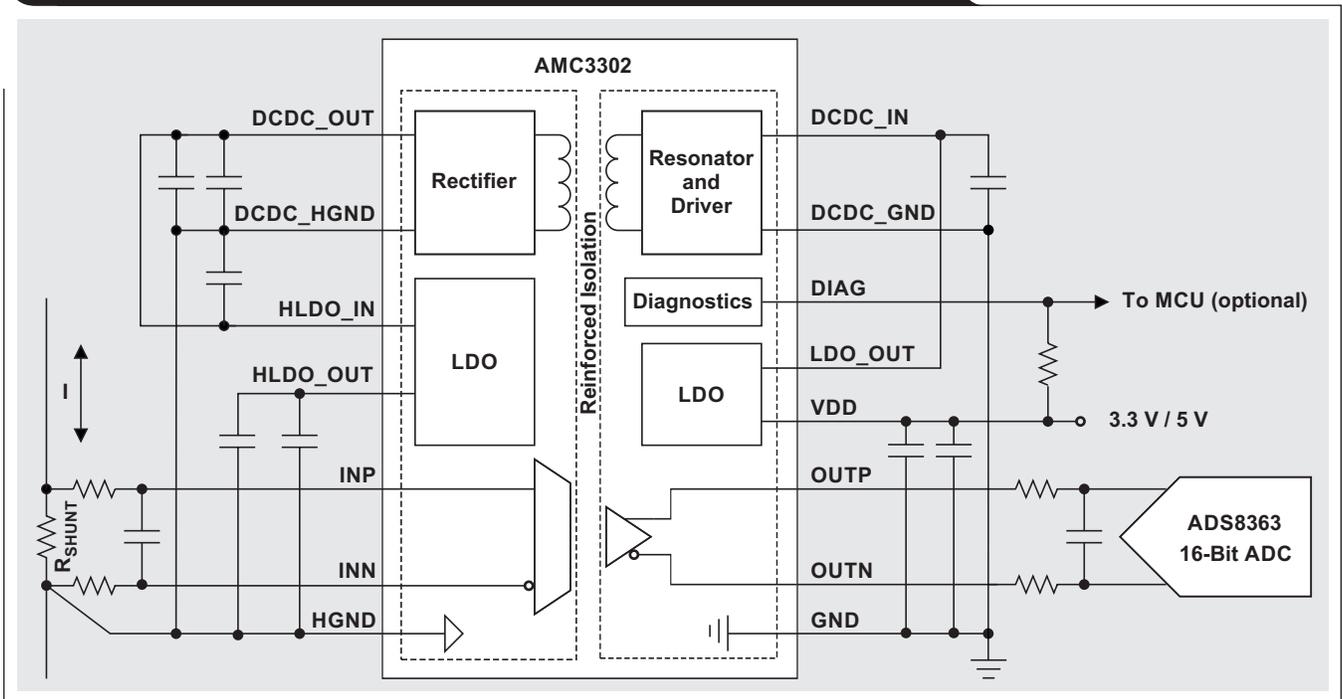


Figure 3. The AMC3302 isolated amplifier with an internal DC/DC converter



voltage range. Determining which input voltage range is right for the application will depend on the magnitude of current being measured and the size of the shunt resistor. In general, systems with high current magnitudes typically require an isolated amplifier with a smaller input range, such as ± 50 mV. Systems with relatively low current magnitudes may benefit from the slightly larger input voltage range of ± 250 mV, which allows for higher signal-to-noise ratios.

There are two equations to consider when selecting the input voltage range: Ohm's law (Equation 1), and the power dissipated in a resistor (Equation 2):

$$V = I \times R \quad (1)$$

$$P = I^2 \times R \quad (2)$$

These two equations govern the trade-off between maximizing the full-scale input range of the isolated amplifier and the amount of power dissipated in the shunt resistor. When supplied with current and resistance values, Equation 1 calculates the voltage drop across the shunt resistor. Try to match this voltage drop as closely as possible to the full-scale input voltage range of the isolated amplifier, as any mismatch between the two values will result in a direct loss of resolution.

Equation 2 quantifies the power dissipated in the shunt resistor. This is important, since shunt resistors will begin to drift (according to their temperature drift specification) from self-heating once the power dissipated through the resistor reaches one-half the rated power dissipation, resulting in a gain error. In order to avoid excessive shunt drift caused by self-heating, it is often best to limit the shunt resistor's nominal power dissipation to be equal to or less than one-eighth the rated power dissipation.

For example, if the current requirement is for a nominal current of 18 A and a maximum current of 52 A. Knowing that there are two options for the linear-input voltage range (± 50 mV and ± 250 mV), as well as the maximum current, it is possible to calculate ideal shunt resistance values to meet the full-scale input range for both choices:

$$\pm 50 \text{ mV: } R_{\text{Ideal}} = 0.96 \text{ m}\Omega$$

$$\pm 250 \text{ mV: } R_{\text{Ideal}} = 4.8 \text{ m}\Omega$$

Finding the closest standard shunt resistor values:

$$\text{For } \pm 50 \text{ mV: } R = 1 \text{ m}\Omega, \text{ or}$$

$$\text{for } \pm 250 \text{ mV: } R = 5 \text{ m}\Omega.$$

Plugging these values into Equation 1 enables the resulting full-scale voltage drop across the shunt resistor to be calculated:

$$\text{For } \pm 50 \text{ mV: } V = I \times R = (52 \text{ A}) \times (1 \text{ m}\Omega) = 52 \text{ mV, or}$$

$$\text{for } \pm 250 \text{ mV: } V = I \times R = (52 \text{ A}) \times (5 \text{ m}\Omega) = 260 \text{ mV.}$$

Notice that the resistance value from the ideal calculation to the closest standard value increased slightly, which

results in a full-scale input voltage range that is larger than the linear full-scale input range of the isolated amplifier. This means that for full-scale current magnitudes, the resulting voltage magnitude will no longer be within the linear region of the isolated amplifier's input. Isolated amplifiers often have an additional input voltage range beyond the linear input voltage range before they begin to clip. Within this region—typically as high as ± 280 mV for ± 250 -mV devices and ± 56 mV for ± 50 -mV devices—the accuracy of the isolated amplifier is not specified in the data sheet; however, the isolated amplifier will continue to output a voltage with accuracy similar to the linear region. This may be acceptable for some applications if the accuracy requirement of the maximum current magnitude is relaxed compared to the nominal measurements.

Next, use the standard resistance values and nominal current magnitudes to calculate the power dissipated in the shunt resistor, assuming that the power dissipation rating in the shunt resistor is 3 W.

$$\text{For } \pm 50 \text{ mV: } P = I_{\text{nom}}^2 \times R = (18 \text{ A})^2 \times (1 \text{ m}\Omega) = 0.32 \text{ W,}$$

$$\text{or}$$

$$\text{for } \pm 250 \text{ mV: } P = I_{\text{nom}}^2 \times R = (18 \text{ A})^2 \times (5 \text{ m}\Omega) = 1.62 \text{ W}$$

For the ± 50 -mV calculation, the nominal power dissipation is less than one-eighth the rated power dissipation. This shunt resistor should not drift significantly from self-heating when measuring the nominal current. The ± 250 -mV calculation results in power dissipation that is over one-half the rated power dissipation, meaning that there could be significant temperature drift when measuring the nominal current range.

Additional measures can be taken to reduce the heat dissipated in the shunt resistor, such as forming large printed-circuit-board planes, or using heat sinks or fans. For very-high current applications, it is possible to maximize the input range by using an operational amplifier to gain the input signal to match the full-scale input range of the isolated amplifier, a method used in Reference 5.

For most applications that measure high nominal current magnitudes, it's a good idea to choose an isolated amplifier such as TI's AMC1302 or AMC3302 with the smaller ± 50 -mV input voltage range.

The last step is to verify that power dissipation at the maximum current magnitude does not exceed the rated power dissipation of the shunt resistor, as exceeding the rated power dissipation could damage the shunt resistor permanently.

$$\text{For } \pm 50 \text{ mV: } P = I_{\text{max}}^2 \times R = (52 \text{ A})^2 \times (1 \text{ m}\Omega) = 2.70 \text{ W}$$

To see measured results similar to the example, please see Reference 6.

Conclusion

When designing an isolated current-sensing circuit in end equipment such as on-board chargers, string inverters and motor drives, there are many decisions to consider when selecting an isolated amplifier. Key elements for consideration are the isolation specifications, the high-side power source and the input voltage range. With the right isolated amplifier that suits system requirements, a design can be achieved without the worry of passing the end-equipment certification, exceeding the absolute maximum analog input voltage ratings or causing excessive self-heating of the shunt resistor.

References

1. Alex Smith, “Best in Class Radiated Emissions EMI Performance with the AMC1300B-Q1 Isolated Amplifier.” Application Report (SBAA438), June 2020.
2. “Isolated amplifiers – Certifications,” for products from Texas Instruments
3. AMC1300 evaluation module (EVM), Texas Instruments
4. Ravi Kiran Raghavendra, “Simplify your isolated current and voltage sensing designs with single-supply isolated amplifiers and ADCs.” TI E2E™ support forums technical article, October 26, 2020.
5. “Shunt-Based, 200A Peak Current Measurement Reference Design Using Isolation Amplifier,” Texas Instruments (TIDA-00445), March 2016.
6. Smith, Alex. “Accuracy Comparison of Isolated Shunt and Closed-Loop Current Sensing,” Application Brief (SBAA464), September, 2020.

Related Web sites

Reference designs:

On-board (OBC) & wireless charger integrated circuits and reference designs

Solar string inverter integrated circuits and reference designs

Motor drives system block diagrams, reference designs and products

Product information:

Isolation solutions from Texas Instruments

AMC1300B-Q1

AMC1302-Q1

AMC3302

SN6501-Q1

TLV704

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