Selecting amplifiers for shunt-based current sensing in 3-phase motor drives

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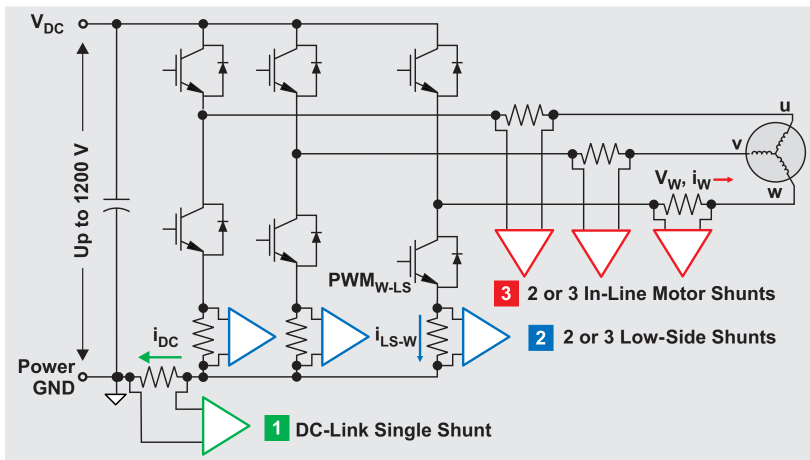
Introduction

Accurate phase-current sensing has a significant impact on the performance of vector-controlled three-phase inverters for industrial motor drives. The motor phase currents can be measured through Hall-effect, fluxgate or transformer-based magnetic sensors, or through shunt resistors. Magnetic sensors offer inherent isolation and a wide current range, while shunt solutions offer cost-effective, highly-linear and high-bandwidth sensing options. Phase currents can be as high as 100 A with three-phase inverters operating from 110 to 690 VAC or from 12 to 60 VDC. To get the motor phase currents, shunts are typically placed either at the DC-link return to GND, between the bottom switch and GND, or in-line with the three-phase power to the motor (see Figure 1).

Figure 1. Current-shunt options in three-phase inverters



Each shunt placement has advantages and challenges, and specific requirements so that the amplifier can convert the small shunt voltage into an analog or digital signal for processing by a microcontroller (MCU). Figure 2 shows the ideal shunt current versus the phase current over one pulse-width modulation (PWM) cycle for each shunt placement. From a system view, the motor in-line shunts offer major performance advantages, while from an amplifier view, the low-side shunts enable lower-cost solutions, as shown in Table 1 on the next page.

Figure 2. Shunt current vs. phase current and common mode depending on shunt placement

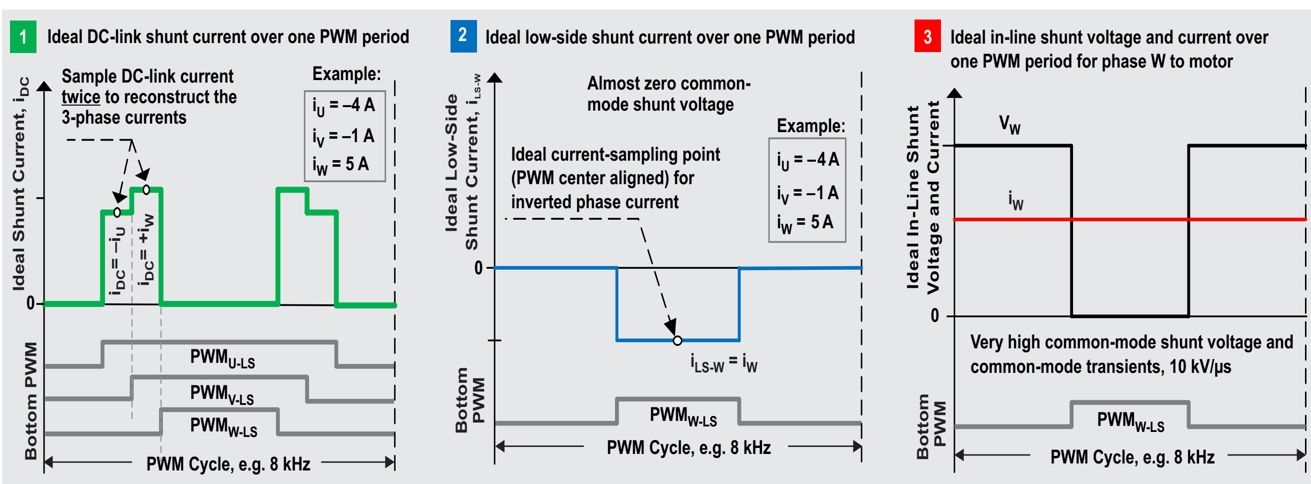


Table 1. Comparison of shunt placement for motor phase-current measurement

	Advantages	Challenges	Accuracy
In-Line motor shunts	• Direct, continuous phase current sense. • Allows averaging phase current over one PWM cycle for higher accuracy and/or a current controller can run twice per PWM. • Detection of phase-to-phase and phase-to-GND shorts.	• Amplifier requires high common-mode input voltage with a high common-mode rejection ratio (CMRR). • AC line-fed inverters typically use an isolated approach.	High
Low-side shunts	• Can detect shoot-through. • Lower system cost: due to near zero common mode input voltage a non-isolated current sense amplifier/op amp can be used.	• Indirect, discontinuous inverted phase-current sense. Can be measured only when low-side switch is on. • Cannot average over one PWM period and run the current controller twice per PWM. • Cannot detect phase-to-GND shorts.	Medium
DC-link single shunt	• Works with both vector control and trapezoidal control. • Applicable to intelligent power modules with common GND. • Lower system cost: due to near zero common mode input voltage a non-isolated current sense amplifier/op amp can be used.	• Requires two measurements synchronized to the PWM pattern in each PWM cycle. • Requires a minimum duration of each active PWM pattern and PWM compensation algorithms to ensure a minimum duration. • Requires an amplifier with a high bandwidth and slew rate.	Low

In shunt-based systems, the shunt resistance and package are a compromise between accuracy, thermal performance, printed circuit-board (PCB) size and cost. In motor drives, the shunt resistance is such that the voltage drop at maximum phase current is typically from ±25 mV to ±250 mV. The subsequent amplifier converts the small bipolar shunt voltage into a typically unipolar output voltage, with bias offset matched to the ADC's 3-V to 5-V input range. Gain settings are typically from 10 to 100.

For each of the three shunt placements, the shunt-resistance tolerance and drift—as well as the amplifier's gain, input offset and related drift—over temperature have similar impacts on accuracy.

Consider an example with a shunt with ±50-mV maximum voltage (100-mV full-scale input range) and assume each parameter should not contribute more than ±0.1% to the absolute error over the industrial temperature range. This requires the amplifier input-offset voltage to be ≤100 µV and the offset drift to be ≤1 µV/°C. The amplifier's gain-set resistors, as well as the shunt, are required to have 0.1% tolerance with a drift of ≤10 ppm/°C. Of course, not all drives require this accuracy and parameters scale. Unlike the gain error, the offset error is often more critical, as it contributes to an absolute error that is independent of the current magnitude, and hence, especially impacts the inverter performance at lower currents.

Placement No. 1: A single DC-link to GND shunt

A single DC-link shunt is more common in low-cost, low-power, vector-controlled fans and pumps than in industrial AC and servo drives. The DC-link current must be measured twice per PWM cycle at two different PWM switching states to reconstruct the three phase currents. The short measurement cycle at small voltages requires amplifiers like the OPA835 from Texas Instruments. This amplifier offers a high large-signal unity-gain bandwidth of at least 20 MHz and high slew rates (>10 V/µs) to settle in <1 µs, as with the solution shown by Reference 1. The method won't work for zero phase voltage since all three PWM duty cycles are 50%, unless extended with sophisticated PWM compensation algorithms.

Placement No. 2: Low-side current shunts

Using low-side current shunts are attractive for compact AC-line-fed inverters up to approximately 5 kW and for 12- to 60-V DC-fed motor drives, where the control MCU is non-isolated and connected to power GND. The shunts might be placed in two or three legs of the three-phase inverter.

The amplifier ideally operates from a single supply, which is the same for the subsequent analog-to-digital converter (ADC). Since the shunt voltage drop is referenced to GND, an input common-mode voltage near the negative rail (GND) is crucial. To decouple from GND bounces during switching, an amplifier in a differential to single-ended configuration will convert the small bipolar shunt voltage into a unipolar voltage, typically 0 V to 3.3 V with 1.65-V mid-bias, to drive the ADC. Key parameters for the amplifier are:

- A rail-to-rail input with a near zero input common-mode voltage.
- A rail-to-rail output.
- A single supply voltage.
- Offset and offset drift: This might not be critical because offset can be measured at each PWM cycle when the low-side switch is off.
- Bandwidth and slew rate: These impact the minimum settling time, which should be smaller than the customer-specific minimum on-time for the low-side switch.

When using three shunts, a workaround for a low-side on-time that is too small is to only consider the two phases with the highest on-time and calculate the third phase. This approach won't work for the two-shunt solution; the amplifier has to settle at least within the minimum on-time specified, typically even at half the minimum on-time since the current is often sampled symmetrically to the PWM.

Table 2 provides example settling times for an amplifier with a unity gain bandwidth of 10 MHz, like the TLV9062.

For a bill-of-materials reduction, amplifiers with internal fixed gain settings like the INAx181 are an alternative.

Table 2. Settling time versus amplifier gain-bandwidth

Operational Amplifier (Op Amp) Unity-Gain Bandwidth	Gain	Band-width	Minimum Slew Rate at 3.3 V	Settling Time to 1%	Settling Time to 3%
10 MHz	20	500 kHz	≥3 V/µs	1.5 µs	1.1 µs
10 MHz	50	200 kHz	≥1.2 V/µs	3.7 µs	2.7 µs

Placement No. 3: In-line motor shunts

Non-isolated in-line phase-current sensing

For 12-V to 60-V DC-fed inverters, non-isolated current-sense amplifiers referenced to GND of DC– are attractive due to their system cost. The major challenge here is the huge common-mode voltage, which is 100- to 1,000-times higher than even the full-scale shunt voltage. This requires amplifiers with:

- Very high DC and AC CMRR for accurate current measurements without long recovery ripple after transients. The DC CMRR should be at least –100 dB and the output should settle within a few microseconds. Table 3 outlines the impact of CMRR.
- A wide common-mode voltage range—from at least –1 V to 70 V for margin during switching and DC-link voltage increase during motor braking.

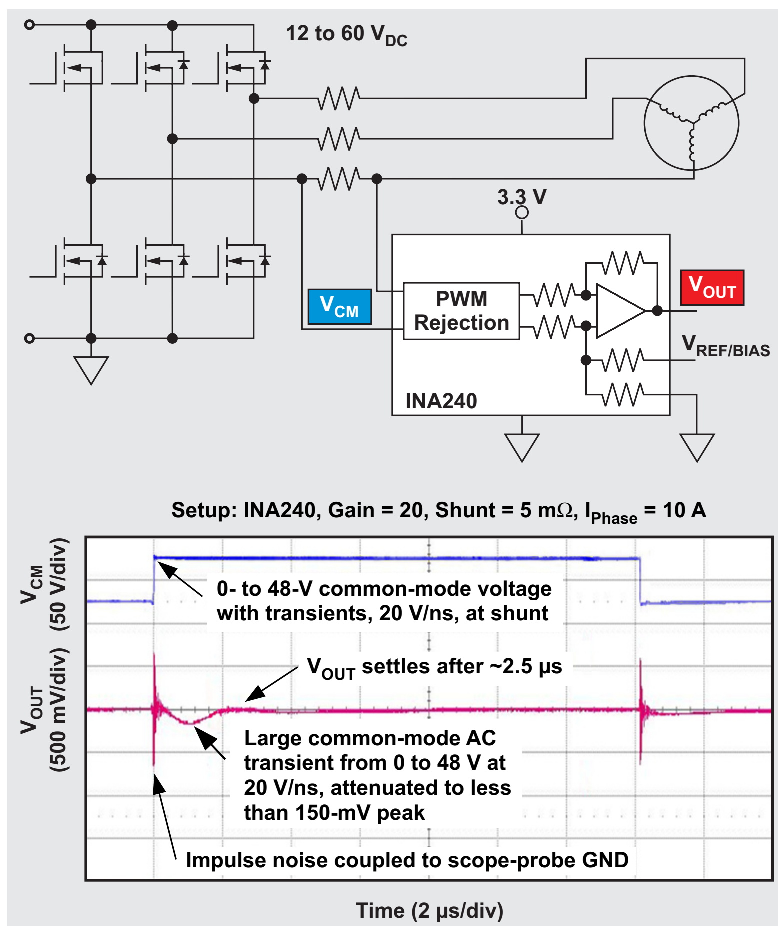
Table 3. Impact of CMRR on accuracy

Parameter	Value	Accuracy versus ±50 mW	Comment
CMRR (DC)	–120 dB	0.1%	At 48-V common mode
CMRR (AC)	–90 dB	3.3%	At 0- to 48-V common-mode transient, fast settling required "PWM rejection"

The amplifier ideally operates from a single 3.3-V supply, which is the same as the subsequent ADC or MCU-embedded ADC. This eliminates the need for clamping diodes to protect the ADC input. An amplifier bandwidth at a configured gain of 400 kHz allows overcurrent detection as fast as ≤1 µs (10% to 90%). It's not possible to compensate for offset and gain error easily in this configuration, especially over the operating temperature range. As outlined before, the offset and offset drift is critical for the inverter's low-current performance and the acceptable offset error depends on the desired current-measurement accuracy.

Figure 3 shows a transient response of a current-sense amplifier with enhanced PWM rejection (the INA240) with a 48-V three-phase gallium-nitride (GaN) inverter. Thanks to high DC and AC common-mode rejection, the phase current settles within around 2.5 µs. Assuming a center-aligned sampling, the minimum PWM on or off time required to accurately measure the corresponding phase current is 5 µs. For lower on/off times, the three-shunt approach enables the third phase current to be calculated from the other two phases with higher on/off times.

Figure 3. In-line current-sense amplifier and transient response over one PWM cycle at 48 V



Isolated in-line phase-current sensing

For AC line-fed inverters with DC-link voltages from 300 to 1,200 VDC, an isolated amplifier or delta-sigma modulator provides accurate phase-current sensing with in-line shunts. The isolation function enables rejection of the large common-mode voltage and transients shown in Table 1. Since industrial motor drives are required to meet International Electrotechnical Commission (IEC) 61800-5-1 electrical-safety requirements, basic or reinforced insulation is required. Basic or reinforced isolated amplifiers and delta-sigma modulators serve this purpose.

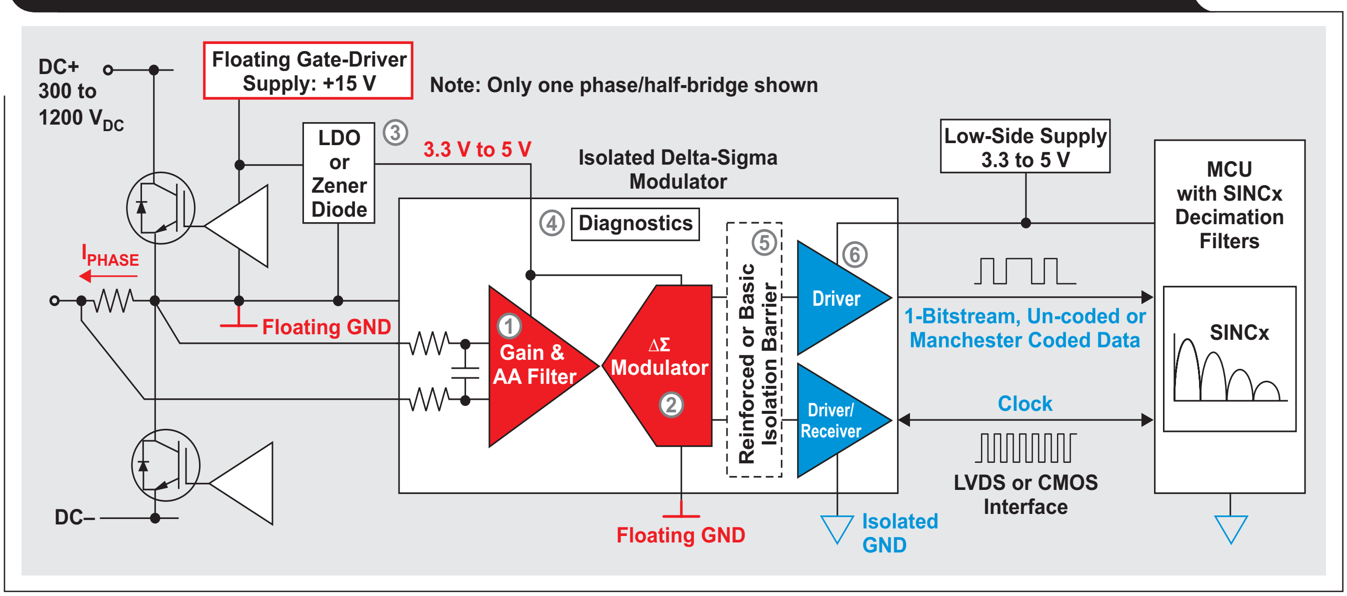
Isolated delta-sigma modulators

Figure 4 shows the isolated phase-current measurement with an in-line shunt and isolated delta-sigma modulator. It can be applied to three phases or two phases with the third phase current calculated accordingly. The floating shunt voltage is low-pass filtered, amplified and fed into a second-order delta-sigma modulator, which is isolated from the output. The isolated output is a bitstream of ones and zeros at the modulator clock frequency, typically from 5 to 20 MHz. A decimation filter in the MCU must process the bitstream to get an accurate high-resolution result.

From a system perspective, isolated delta-sigma modulators should offer:

1. A gain amplifier with an anti-aliasing filter with:
   - A ±50-mV input range that reduces shunt losses by 80% compared to the traditional ±250-mV range.
   - Very low gain, offset and related drift are crucial for accuracy, since it is difficult to compensate for them. A very-low 50-µV offset with 1-µV/°C drift contributes to less than 0.11% error over a temperature range from 25°C to 85°C.
   - An integrated anti-aliasing filter attenuates noise above half the modulator clock frequency to avoid it folding back and impacting accuracy in the band of interest.
   - The common-mode input voltage should be at least half the negative full-scale input range.
2. A delta-sigma modulator running a 20-MHz clock, to enable highly-accurate, highly-linear current sensing at low latency. Modulators with the Manchester-coded bitstream option enable easier clock routing from the processor to each of the three modulators.
3. A wide-range high-side supply voltage and low current consumption, ideally with an integrated LDO such as the AMC1304, to enable use of the floating-gate drive supply.
4. A diagnostic function that detects loss of high-side power to avoid unpredictable measurements.
5. Basic or reinforced isolation, with high immunity against electromagnetic fields and high common-mode transient immunity (CMTI) of at least 10 kV/µs to reject switch-node transients.
6. A CMOS or LVDS digital interface option: In noisy environments or for longer traces, LVDS offers higher common-mode noise immunity.

Figure 4. In-line shunt-based phase-current sensing with an isolated delta-sigma modulator



The processor's decimation low-pass filter, such as a sinc filter, sets the bandwidth and resolution of the output signal by cutting off high-frequency noise. The effective number of bits (ENOB) and settling time increase with sinc filter order and oversampling ratio; see Figure 5. The advantage of digital filters is that resolution versus bandwidth and settling time can be configured in software, and two or more filters can be applied to the same bitstream. This enables a high-resolution phase current for accurate control (for example, 12 ENOB with a $sinc^3$ filter and 64-times oversampling) and very-fast overcurrent detection (for example, 1.2 µs with a $sinc^3$ filter and 8-times oversampling).

Isolated amplifier

Figure 6 shows the phase-current sensing with an isolated amplifier. The non-isolated subsystem of the isolated amplifier (drawn in red) is the same as with the isolated delta-sigma modulator in Figure 4. The main difference is the inclusion of an output filter (subsystem drawn in blue). An active low-pass filter with fixed cut-off frequency removes the high-frequency quantization noise in the bitstream and provides a high-linear differential analog output. The system considerations under items 1 through 5, that a delta-sigma modulator should have, also apply to isolated amplifiers. However, the analog bandwidth and settling time are hardware-fixed and depend on the device-specific oscillator clock and low-pass filter of the isolated amplifier.

Figure 5. ENOB vs. OSR and settling time for a 20-MHz modulator clock (AMC1306)

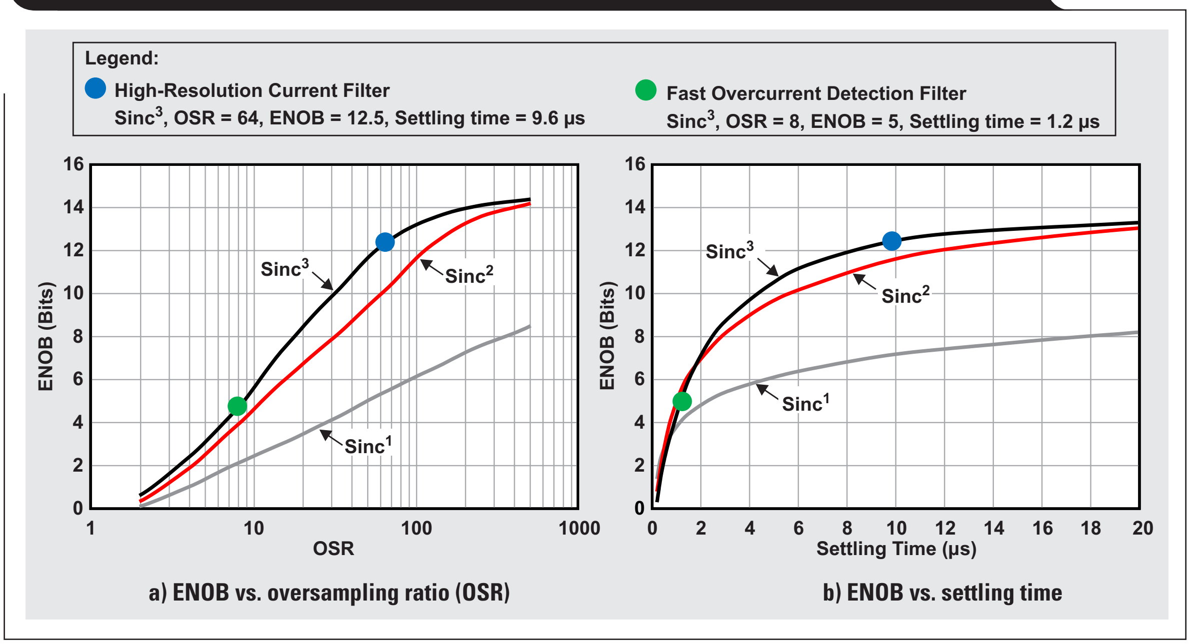


Figure 6. In-line shunt-based phase-current sensing with an isolated amplifier

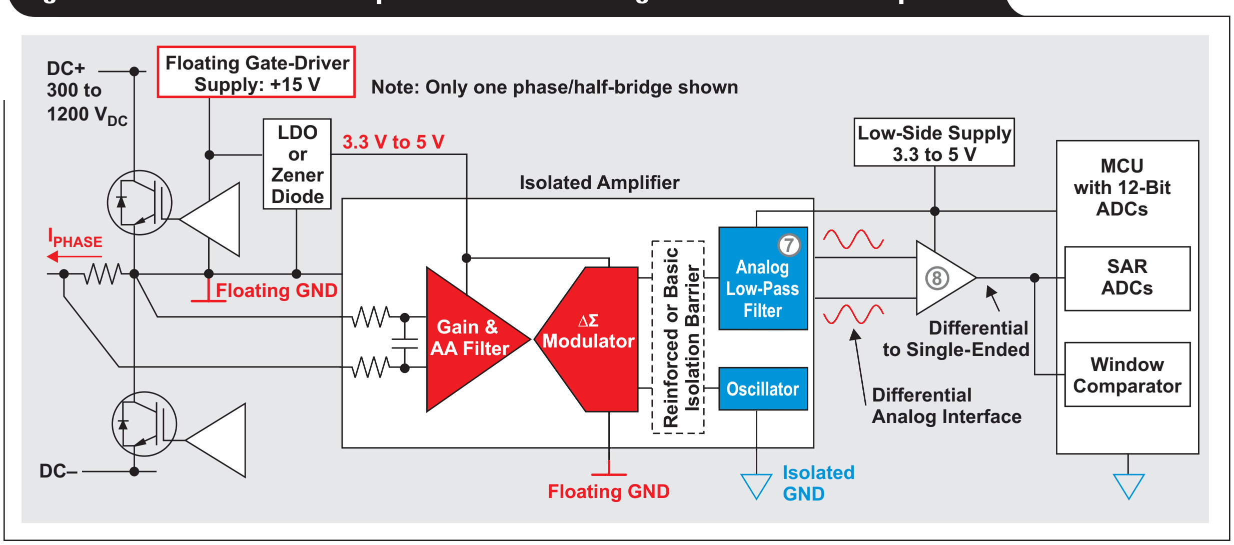


Table 4. Comparison between an isolated amplifier and isolated delta-sigma modulator

Parameter	Isolated Amplifier	Isolated Delta-Sigma Modulator
Resolution/accuracy	Three conversion stages: System resolution also impacted by external ADC, typically ≤12 bit.	Single analog-to-digital conversion: 16-bit resolution with 14-bit accuracy (ENOB) possible, pending digital filter configuration. See Figure 5.
Bandwidth/settling time	Fixed. High-performance amplifiers offer 300-kHz bandwidth and less than 3-µs settling time.	Flexible. Pending digital filter on processor. See Figure 5.
Short-circuit detect	Requires additional analog hardware (window comparator).	No additional hardware required; calculated on the processor.
Interface to processor	Analog differential interface: easy to interface to any MCU with an embedded SAR ADC, but requires an additional amplifier.	CMOS or LVDS interface. Requires a higher-performance MCU/ microprocessor unit (MPU) with an integrated delta-sigma interface or field-programmable gate array (FPGA).
EMC immunity	Medium, due to analog differential output signals.	High to very high, due to digital signals and LVDS interface option.

The isolated amplifier-based phase-current sensing system has three conversion stages: the isolated amplifier, an additional differential-to-single-ended amplifier and typically a singled ended 12-bit SAR ADC. Short-circuit detection requires an additional window comparator per phase.

A major system advantage is the simple analog interface to a wide range of MCUs with an embedded ADC. For single-ended ADCs, an additional op amp is needed—one that will not degrade performance. For better noise immunity, place the op amp close to the MCU to keep the analog traces differential as long as possible. From a pure system performance perspective, the isolated delta-sigma modulator system is superior. Table 4 provides a comparison.

Conclusion

A TI reference design is available for each system configuration described in this article, with detailed hardware design guidelines and system test results.

References

1. "Current Sensing with <1-µs Settling for 1-, 2- and 3-Shunt FOC in 3-Phase Inverter," Texas Instruments Reference Design (TIDA-00778).
2. Harald Parzuber, "High precision in motor drive control enables industrial advances." Texas Instruments white paper (SLYY117), 2017.
3. Jason Bridgmon and Carolus Andrews, "Current Sensing for Inline Motor-Control Applications," Texas Instruments application report (SBOA172), October 2016.
4. Scott Hill, "Low-Drift, Low-Side Current Measurements for Three-Phase Systems." Texas Instruments application note (SBOA161B), 2017.

TI reference designs

Current Sensing with <1-µs Settling for 1-, 2- and 3-Shunt FOC in 3-Phase Inverter (TIDA-00778)

48V 3-Phase Inverter with Shunt-Based In-Line Motor Phase Current Sensing Reference Design (TIDA-00913)

Reinforced Isolated Phase Current Sense Reference Design with Small Delta Sigma Modulators (TIDA-00914)

High-Bandwidth Phase Current and DC-Link Voltage Sensing Reference Design for Three-Phase Inverters (TIDA-01541)

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