Application Note

Precise Current Sensing for Low Voltage Drones, Robotics, and Servo Drives

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ABSTRACT

This application note compares two shunt-based, in-phase current sensing designs for three-phase motor control inverters operated from 24V to 100V DC bus voltages: the AMC0106M05 and AMC0106M25 functionally isolated delta-sigma modulators and the INA241A non-isolated current sense amplifier with enhanced PWM rejection. The AMC0106M05 supports a ±50mV and the AMC0106M25 a ±250mV linear input range; the INA241A operates over a -5V to 110V common-mode input range. Typical applications are battery-operated drones, servo drives, and collaborative or humanoid robots powered from sub-60V supplies. Both devices are shown to achieve sub-1% measurement accuracy over the full industrial temperature range, meeting the requirements of precision motor control.

Key trade-offs between the two architectures are examined across resolution, noise immunity, propagation delay, and MCU interface requirements. The AMC0106Mxx dual-ground architecture is shown to provide inherent PWM switching noise immunity without blanking periods, achieving greater than 12-bit ENOB through oversampling with a Sinc3 filter at OSR32–128, at the cost of a dedicated high-side supply and an MCU with sigma-delta filter channels. The INA241A is shown to achieve 9 to 11-bit ENOB with a 0.25µs propagation delay at 1MHz bandwidth using a switched-capacitor PWM rejection filter, requiring only an external ADC and voltage reference. Both designs offer small total sizes, making these designs excellent choices for space-constrained motor control designs.

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1 System Introduction

Precise current sensing in low-voltage motor control applications typically operated with DC bus voltages from 24V up to 100V present many unique design challenges that require careful consideration of which current sense device is most practical for the system. This application note focuses on shunt-based, in-phase current sensing designs. Compared to indirectly sensing the motor current through low-side shunts, in-phase current sensing offers significant system advantages. Due to the continuous motor phase current measurement, in-phase sensing allows more precise, lower noise current sensing through over-sampling, especially at small PWM duty cycles. In-phase sensing also enables the PID current controller to run twice per PWM to get a higher current loop bandwidth for faster torque response. In addition, in-phase sensing allows a fast phase-to-phase and phase-to-GND short-circuit detection to make the system more robust. Another system benefit of in-phase sensing is that the source of the low-side Si-FET or GaN-FET is directly referred to the system ground. The lack of additional parasitic impedance helps reduce switch node ringing during PWM switching compared to low-side shunt-based designs.

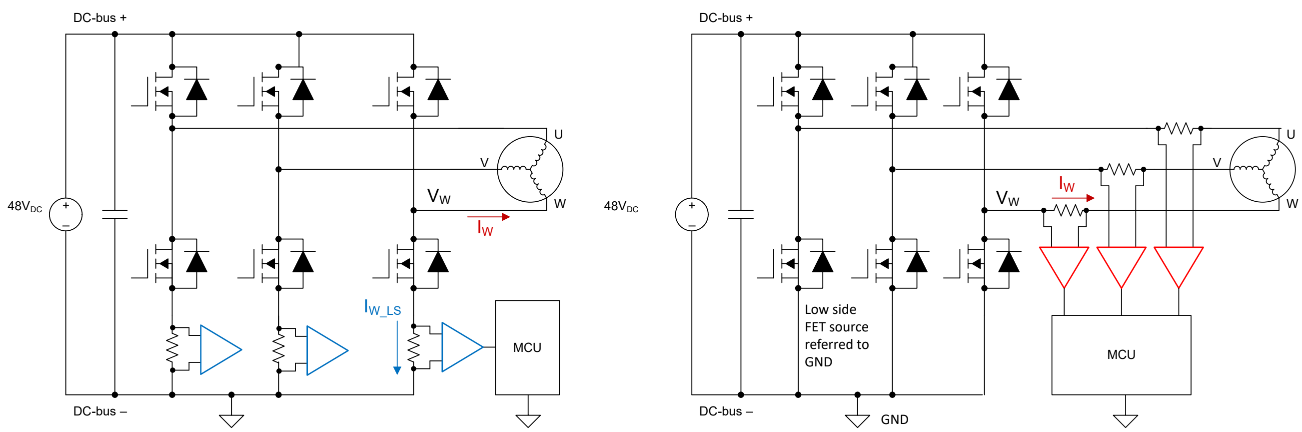


Figure 1-1. Three-Phase Motor Current Sensing Architecture: Low-Side Shunt-Based (Left Hand) and In-Phase Shunt-Based (Right Hand)

While low-side shunt-based sensing has near zero common mode voltage versus system GND, in-phase current sense devices are operated at PWM switched common mode voltages determined by the DC bus. In addition, in-phase current sense devices need to have a high immunity (CMTI, PWM rejection) against common mode voltage transients with slew rates of 10V/ns or higher along with overshoot above the DC bus and undershoot below system ground to accurately measure the phase current even during PWM switching, as shown in Figure 1-2 with a DC bus voltage of 48V.

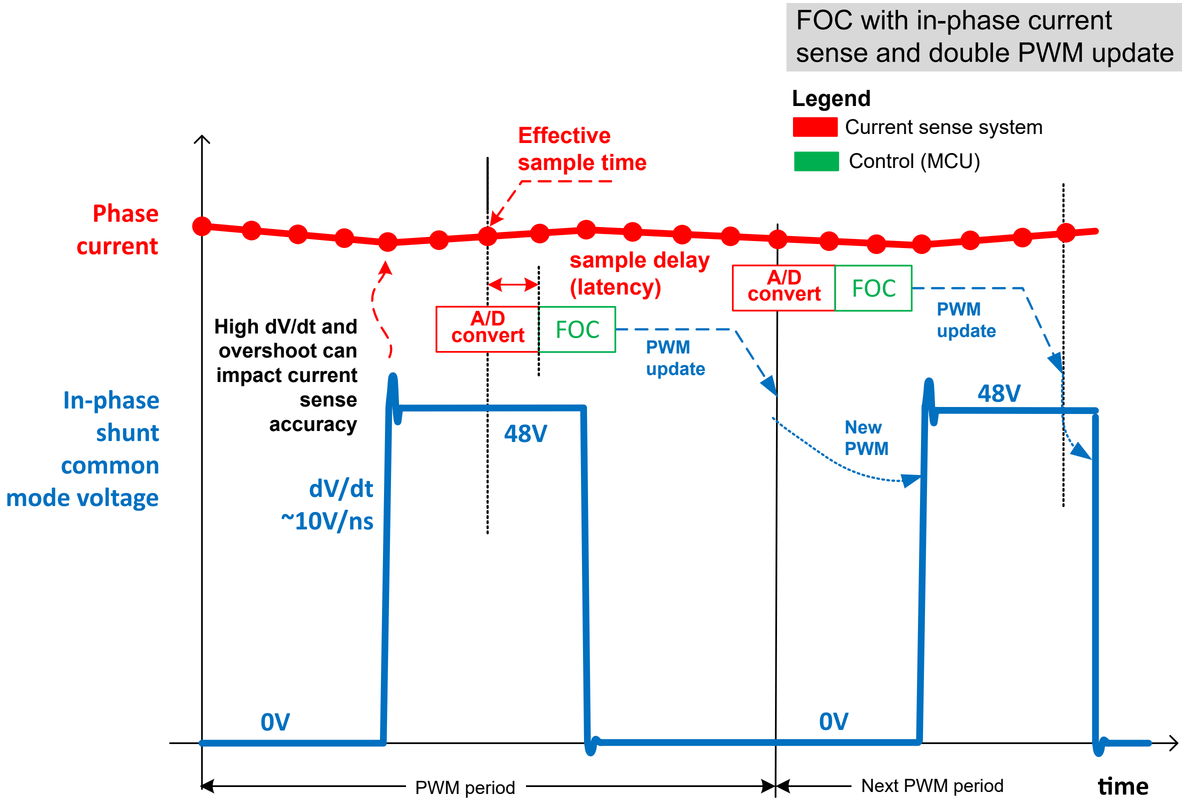


Figure 1-2. In-Phase Shunt Common Mode AC Voltage Over One PWM Cycle with Double PWM Update

2 Inline Current Sense Device Options

For shunt-based systems isolated and non-isolated current sense devices which can handle high common mode voltage and high common mode voltage transients can be used.

The choice between isolated and non-isolated current sensing architectures involves trade-offs between accuracy, effective resolution and signal to noise ratio, propagation delay, system-level noise immunity, analog or digital interface to the microcontroller and more.

Let us look into TI's latest galvanically isolated modulator AMC0106M05 and AMC0106M25, as well as the non-isolated INA241A bidirectional ultra-precise current sense amplifier with enhanced PWM rejection. Both devices are capable of achieving better than 1% accuracy requirements demanded by precision motor control applications such as battery operated low-voltage drones, and 24V to 60V robotics and servo drives.

2.1 Common-Mode Voltage Versus Working Voltage

To truly understand the functionality and requirements of functional isolated and non-isolated devices, we must first digest the specifications associated with these devices and clarify the differences in how the device operational ranges are denoted. Depending on whether you use an isolated or non-isolated device, your terminology can differ but the use-case and meaning remains the same.

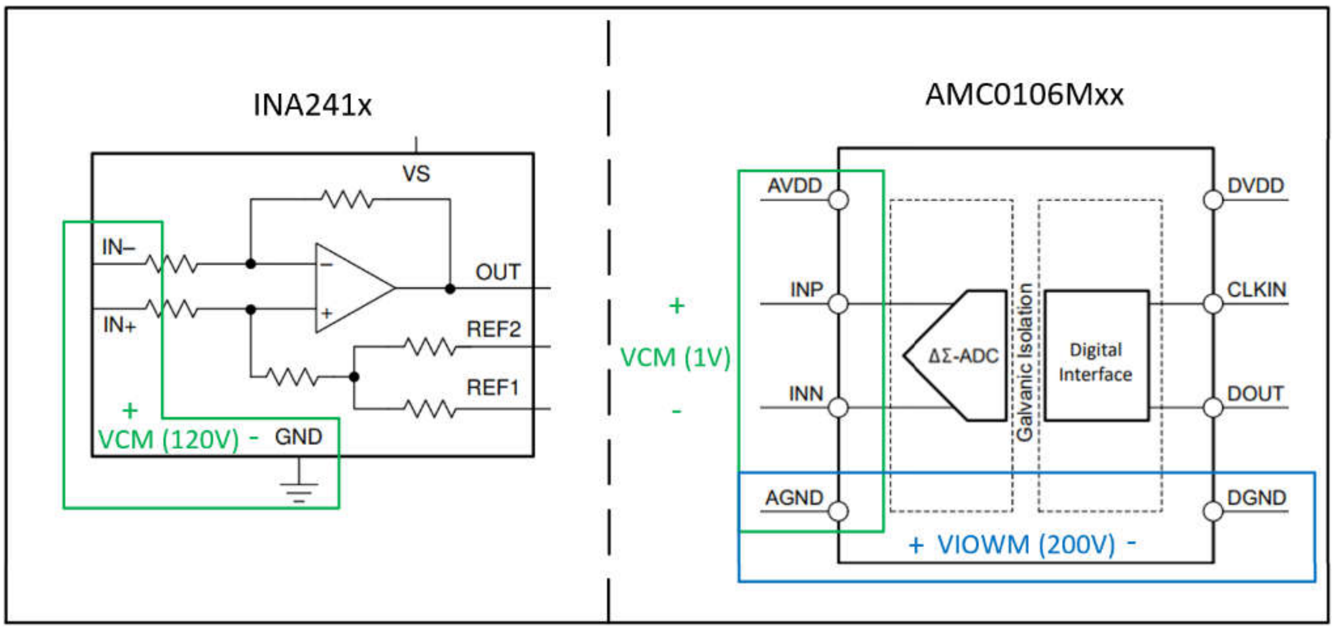


Figure 2-1. Correlation Between VCM and VIOWM in Isolated and Non-Isolated Systems

For non-isolated devices, Figure 2-1 highlights how the common-mode input voltage describes the allowable input pin-voltage relative to the system ground. This spec determines the common mode voltage range that can be applied without compromising the performance of the device. In the case of the INA241 the preferred range is -5V to 110V for best performance, and -20V to 120V as the absolute maximum range where the device operates, but with degraded performance.

Isolated designs like the capacitively isolated AMC0106M05 (±50mV linear input range) and AMC0106M25 (±250mV linear input range) typically use the working voltage specification to assert the range the device operates at before the isolation barrier degrades and the device fails, as shown in Figure 2-1. The working voltage specifies the voltage difference allowed between the two fully isolated grounds on the device, AGND and DGND. AMC0106 has a maximum working voltage of 200Vrms or 280Vdc between these two grounds which handle the PWM switched common mode voltage of the shunt versus the system ground. Different from the non-isolated current sense amplifier INA241A, the AMC0106Mx INP and INN differential input pins have a much smaller common-mode input voltage range relative to the analog AGND, VCM = 1V to -160mV (AMC0106M25) and VCM = 1V to -32mV (AMC0106M05). Therefore, the AMC0106Mx AGND must be connected to one of the terminals on the shunt, depending on the desired current direction.

In application, these two different specifications address the core problem of determining the maximum allowable voltages in the motor control system. Whether dealing with common-mode voltage in non-isolated designs or working voltage in isolated architectures, engineers must verify that devices in their system remain within specified limits to maintain accurate measurements. At a fundamental level, the key difference lies in how each architecture handles these common mode voltage stresses. For example, isolated devices like the AMC0106M05 provide inherent protection through galvanic isolation, while non-isolated designs require careful system-level design to manage the voltage difference. This is typically an important distinction in higher voltage systems; however, in low-voltage, approximately 48V designs, this becomes less critical because it falls well below the maximum range of both designs.

2.2 Device Architecture Comparison

2.2.1 INA241: Non-Isolated Analog Amplifier with Inherent PWM Rejection

The INA241 utilizes a high-performance analog amplifier architecture optimized for speed and simplicity. The non-isolated design of the INA241 has one ground reference used for both the internal circuitry and output, simplifying PCB layout and reducing component count. The analog output interface provides immediate access to amplified current signals without requiring complex digital filtering or processing. The streamlined architecture of the device contributes to an impressive 1MHz bandwidth specification, making the INA241 an excellent choice for applications requiring low latency in the control loop. The analog interface allows for straightforward integration with existing analog-to-digital converters and control systems. However, in these motor control systems, analog devices like current sensing amplifiers typically employ blanking periods, which is an approximately 2us to 3us dead time where no measurement is taken so that artifacts and noise spikes during PWM switching are not counted. These blanking periods can cause missed readings and faulty data as PWM switching frequencies increase. To counter this, INA241 uses a switched-capacitor filter architecture to attenuate the switching noise. This filter dynamically adjusts the sampling rate based on the changes in PWM frequency, up to 125kHz or if each of the common mode transients are separated by a >3us interval.

Another benefit to the INA241 is a PWM rejection feature, and high CMRR. However, in these motor control systems, analog devices like current sense amplifiers see large common-mode ΔV/Δt transients. Large ΔV/Δt common-mode transients associated with PWM signals are employed in applications such as motor or solenoid drive and switching power supplies. The disturbances that can occur at the output of a current sense amplifier from common-mode transients causes erroneous measurements and impose limitations when the output is valid. The INA241x is designed with an enhanced PWM rejection feature, which is a high common-mode rejection technique that holds the device output for 1µs thereby preventing the common-mode disturbance from propagating to the output. If another common-mode transient occurs during the following 3µs, the INA241x relies on high BW and AC CMMR to attenuate the effect of common-mode transient. The enhanced PWM rejection is achieved up to a PWM frequency of 125kHz or if common-mode transient edges are separated by a 3µs interval or more. As a result, this makes system design simple with INA241x. The high AC CMRR, in conjunction with signal bandwidth, allows the INA241x to minimize output disturbances and ringing during common-mode transitions when compared against traditional current-sensing amplifiers.

2.2.2 AMC0106: High CMRR Functionally Isolated Delta-Sigma Modulator

The AMC0106 employs a high-performance isolated delta-sigma modulator architecture that provides several unique advantages. The functional isolation of the device creates a complete galvanic isolation between the high-voltage sensing inputs in-line with the AC motor and the low-voltage digital interface, eliminating ground loop concerns and providing enhanced safety. The device outputs a digital bit stream that communicates directly with modern processors, enabling exceptional noise immunity during data transmission. Also note that the AMC0106 employs separate high-side and low-side ground references where GND1 is tied to the high voltage side and the input stage does not see the common-mode transients. This dual-ground architecture inherently rejects PWM switching noise because high-frequency switching artifacts remain isolated on the high-side ground and cannot couple into the digital communication path, all without any circuit design techniques needed for the purpose of PWM rejection. This design provides exceptional immunity to the switching noise prevalent in motor drive applications, especially as we see switching speeds continue to increase.

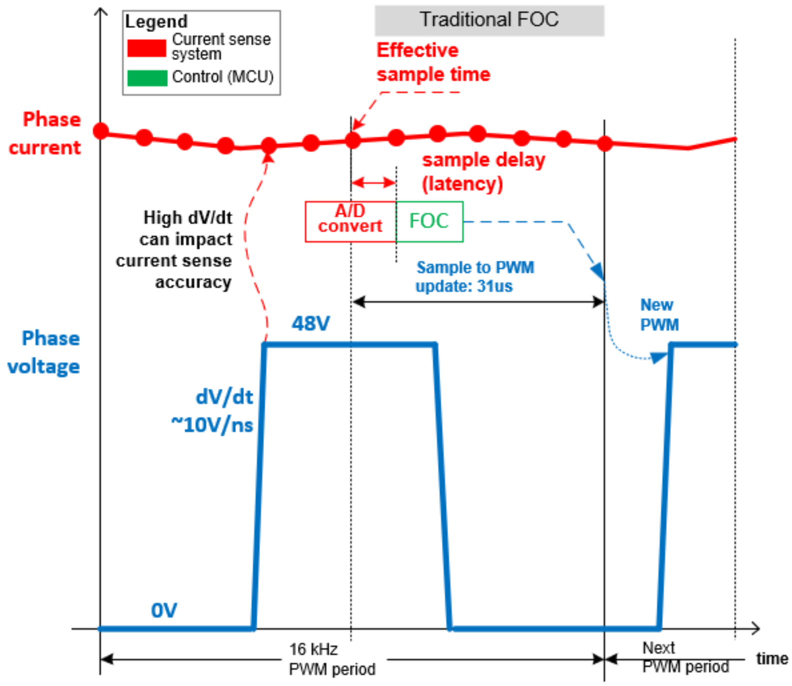


Figure 2-2. Current Sampling for Closed-Loop Phase Current Control and Short-Circuit Detection

Many analog designs today have to implement blanking periods to counter the noise spikes that occur during switching cycles. As switching frequencies increase, the PWM cycle time shrinks, and the fixed blanking period takes up a larger percentage of the available time, potentially leading to issues with proper data acquisition. Texas Instruments' AMC0106M05 and AMC0106M25 modulators have a high CMTI of 150V/ns, which allows continuous sampling at all times and inherent noise immunity due to the functional isolation of the device, meaning no blanking period is needed. This allows for continuous measurement along the entire PWM switching cycle, leading to knowledge of the motor status at all times.

2.3 Performance Benefits Analysis

2.3.1 Accuracy and Precision

Both devices achieve excellent sub-1% measurement error, meeting the stringent requirements of precision motor control applications. However, the digital architecture of the AMC0106M05 provides inherent advantages in maintaining noise and resolution. The isolated delta-sigma modulator delivers exceptional resolution through oversampling and digital filtering, while the digital interface eliminates analog signal degradation that can occur in long trace routing. As seen in Figure 2-3, AMC0106 can achieve 14 effective number of bits, the highest resolution in the market today! This increased resolution allows for less torque ripple which enables holding a position more accurately. more precise movements as well as less jitter during steady-state operations.

The INA241 cannot achieve the same resolution, but still boasts a very robust 11-bit achievable ENOB. With that in mind, The INA241's analog architecture provides immediate signal availability with minimal processing requirements, however analog signals are more susceptible to board-level noise and interference in electrically harsh environments. This architecture allows the INA241 to have a propagation delay of only 0.25us at a 1MHz bandwidth while the AMC0106's extra filtering requires a 2.4us to 9.6us propagation delay but with protection against the noise coupling.

2.3.2 Noise Immunity

The INA241 incorporates enhanced PWM rejection filtering in the device, allowing the device to automatically blank the signal when needed during PWM switching to time current measurements and apply the proper filters and minimize the influence of switching transients. This allows INA241 to deliver accurate current measurements despite significant PWM-induced noise.

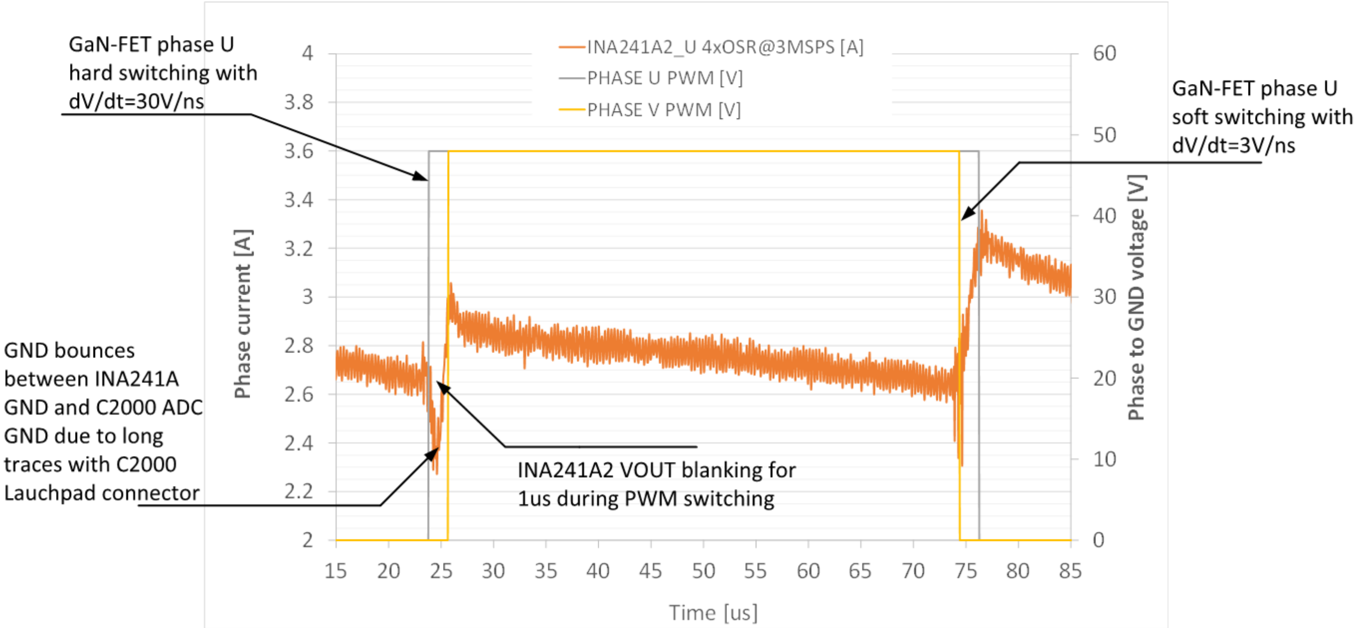


Figure 2-3. INA241 with Blanking Period and High PWM Rejection Filtering Architecture with 4x Oversampling and Averaging at 3MSPS ADC with Latency of 500ns

Similarly, AMC0106M05 demonstrates exceptional noise immunity through multiple mechanisms. The galvanic isolation of the device prevents PWM switching noise induced errors, while the digital bit stream output remains immune to analog interference during signal transmission. The dual-ground architecture provides exceptional PWM rejection by isolating switching noise on the high-side ground plane.

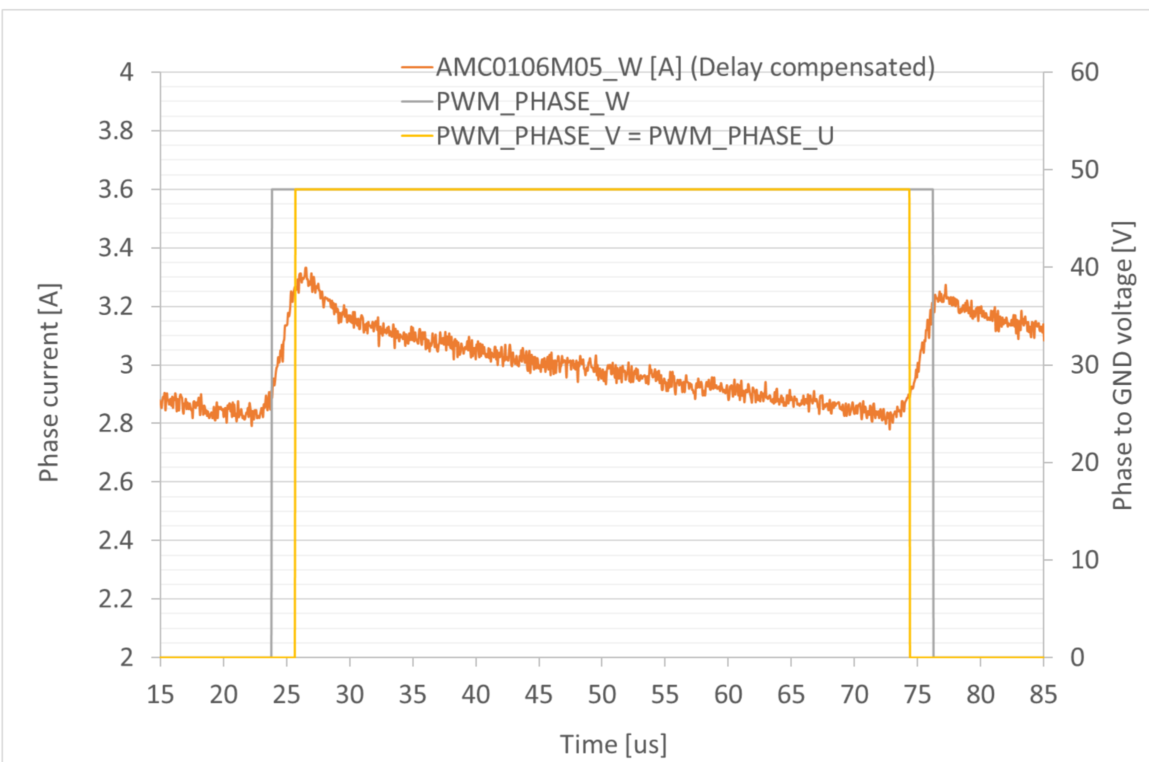
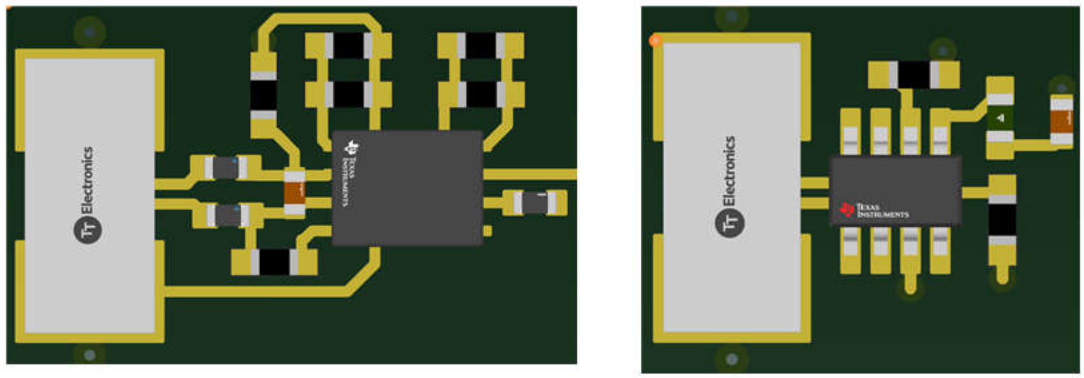


Figure 2-4. AMC0106 with Separate Grounds for High-Side and Low-Side Allowing for Best Noise Performance

2.3.3 Size



AMC0106M05/25 + All Peripherals
Total BOM Footprint: 32.5mm^2

INA241A3 + All Peripherals
Total BOM Footprint: 29mm^2

Figure 2-5. Texas Instruments Offers Very Competitive Designs at Equally Impressive Sizes

Both AMC0106 and INA241 offer very competitive total design sizes of 32.5mm^2 and 29mm^2, making them practical for space constrained drones, robotics, or low voltage servo drive-based motor-control applications.

2.3.4 Design Considerations

The AMC0106 has two key requirements for designers to keep in mind for implementation. First, to provide the high immunity to noise, the device contains an isolation barrier, meaning separate power is needed for the "high" and "low" sides of the device. The most common way to overcome this hurdle is to use the high-side gate driver supply. Second, for up to 14 bits of resolution and direct interfacing with the MCU, the AMC0106 is a modulator device requiring a processor with built in Sigma-Delta Filter Channels. The INA241 provides simplicity in implementation by only requiring an ADC to convert the analog output to the digital one needed. A reference voltage also helps with achieving the best accuracy possible with the device.

3 Summary

The AMC0106M05 isolated current sense modulator and the INA241 non-isolated current sense amplifier each offer unique advantages for precision motor control applications. The AMC0106M05's isolated delta-sigma architecture provides inherent immunity to ground loops, PWM switching noise, and other electrical disturbances through galvanic isolation and dual-ground design. This allows the device to maintain exceptional accuracy and resolution without requiring external blanking or timing coordination. Conversely, the high-performance analog approach of the INA241 prioritizes speed and simplicity, complemented by advanced PWM rejection filtering that minimizes the impact of switching transients.

Technology	**Shunt + AMC0106Mxx**	**Shunt + INA241x**
Example device	AMC0106M05	INA241A3
Evaluation Module	BP-AMC0106-LMG-MD	INA241AEVM
Current range (FSR)[8]	scalable up to ±200A	scalable up ±200A
Overload current	high (18x FSR)	high (18x FSR)
Accuracy (-40..85°C, TYP)	<1%	<1%
ENOB (SNR)	>12bit	9 ..11-bit
Bandwidth	40kHz - 160kHz (Sinc3 OSR32-128)	1MHz
Propagation delay	medium (2.4 .. 9.6us) due to Sinc3 filter	low (0.25µs)
Immunity to GND noise	high (digital interface)	medium (analog interface)
PWM rejection	high (Functional isolation)	medium
Isolated supply	Yes	no
Other requirements	MCU with sinc filter AND high side power needed	Voltage reference for best accuracy

4 References

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