

## Measurement Techniques for Industrial Motion Control

by Nicola O'Byrne, senior applications engineer, Analog Devices, Inc.

Industrial motion control covers a breadth of applications, ranging from inverter-based fan or pump control, to factory automation with more complex ac drive control, to advanced automation applications such as robotics with sophisticated servo control. These systems require sensing and feedback of a number of variables, such as motor winding current or voltage, dc link current or voltage, rotor position, and speed. The selection of variables and the required measurement precision depends on the end application demands, the system architecture, target system cost, or system complexity, amongst other considerations such as value add features like condition monitoring. With motors reportedly consuming 40% of worldwide energy, international regulations have increased the focus on system efficiency across the entire range of industrial motion applications, increasing the importance of these variables, especially current and voltage.

This article focuses on current and voltage sensing in various motor control signal chain topologies according to motor power rating, system performance requirements, and end application. In this context, motor control signal chain implementations differ by sensor choice, galvanic isolation requirements, analog-to-digital converter (ADC) choice, system integration, and system power and ground partitioning.

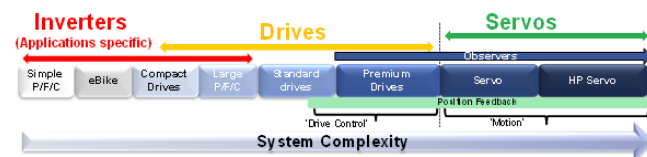


Figure 1. Industrial Drive Application Spectrum

### INDUSTRIAL DRIVE APPLICATION SPECTRUM

Motor control applications can range from simple inverters to complex servo drives, but all include motor control systems with a power stage, a processor that drives a pulse-width modulator (PWM) block with differing levels of sensing and feedback. A simplified view of the application spectrum is shown in Figure 1, illustrating systems with increasing complexity as one moves from left to right across this spectrum, from simple control systems like pumps, fans, and compressors that can be implemented without precision

feedback and just use a simple microprocessor. As system complexity increases, moving toward the higher end of the spectrum, complex control systems require precision feedback and fast communications interfaces. Examples of these would be sensed or sensorless vector control of induction motors or permanent magnet motors, and high power industrial drives designed for efficiency—shown in Figure 1 as large pumps, fans, and compressors. At the highest end of the spectrum, complex servo drives are used in applications such as robotics, machine tools, and pick and place machines. Sensing and feedback of variables becomes more critical as the system becomes more complex.

### DRIVE ARCHITECTURES—SYSTEM PARTITIONING

There are many challenges associated with designing systems to address the variety of applications within the industrial motion control space. A generic motor control signal chain is shown in Figure 2.

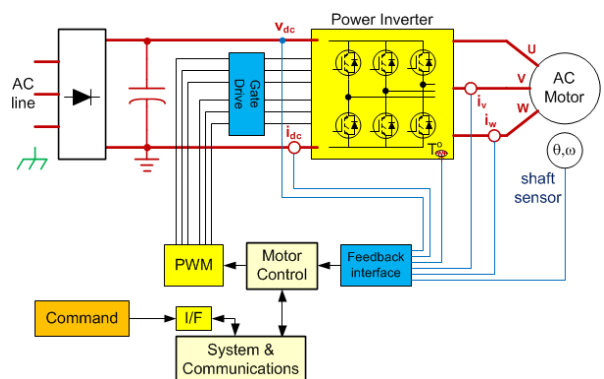


Figure 2. Generic Motor Control Signal Chain

Of critical concern are isolation requirements, and these usually have significant influence on the resulting circuit topology and architecture. There are two key factors to consider: why to isolate and where to isolate.

The classification of isolation required will be dictated by the former. The requirement may be high voltage safety isolation (SELV) to protect against human shock, or functional isolation to level shift between nonlethal voltages, or isolation for data integrity and noise mitigation purposes. Where to isolate is often determined by the expected system performance. Motor control is generally a harsh, electrically noisy environment, with designs commonly experiencing large common mode voltages of several hundred volts, potentially switching at more than 20 kHz with very high transient dv/dt rise times. For this reason, both higher performance systems and high power inherently noisier

systems will usually be designed with the power stage isolated from the control stage. Whether the design has a single or dual processor approach can also have an influence on where to isolate. In systems that are both lower performance and low power, it is common to isolate at the digital communication interface meaning the power and control stages are on the same potential. Lower end systems have lower bandwidth communications interfaces to isolate. Traditionally, it has been challenging to isolate the communications interface in high end systems due to the high bandwidths required and limitations of traditional isolation technologies, but this is changing with the advent of magnetically isolated CAN and RS-485 transceiver products such as those from Analog Devices available at [www.analog.com/icoupler](http://www.analog.com/icoupler).

Two critical elements in high performance closed-loop motor control designs are the PWM modulator outputs and the motor phase current feedback. Figure 3a and 3b illustrate where the safety isolation is required depending on whether the control stage shares the same potential as the power stage, or is referenced to earth ground. In either case, the high-side gate driver and the current sense node need to be isolated, but the class of isolation is different—in Figure 3a, only functional isolation of these nodes is necessary, while in Figure 3b, human safety (that is, galvanic) isolation of these nodes is critical.

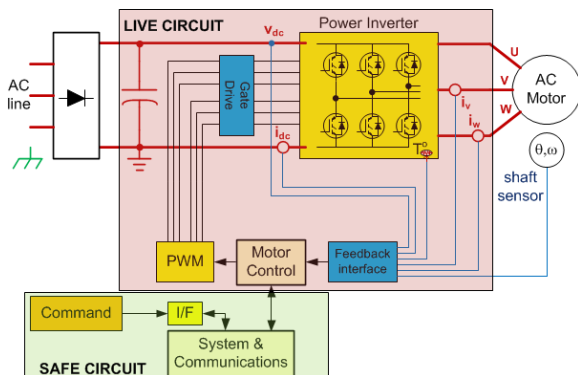


Figure 3a. Control Stage Referenced to Power Stage

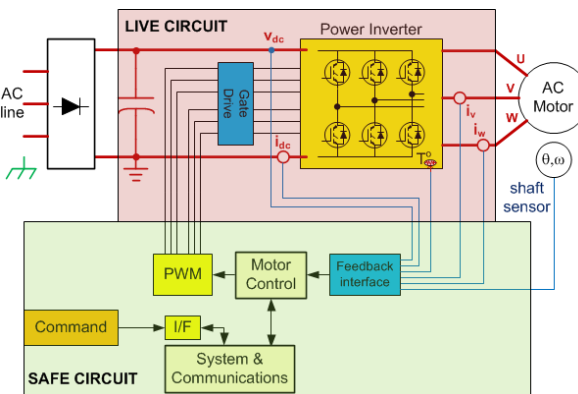


Figure 3b. Control Stage Referenced to Earth

## MEASUREMENT TECHNIQUES AND TOPOLOGIES FOR CURRENT AND VOLTAGE SENSING

Signal chain implementations to sense current and voltage differ by sensor choice, galvanic isolation requirements, ADC choice, and system integration in addition to system power and ground partitioning as already outlined. Signal conditioning to realize a high fidelity measurement is not trivial. For example, recovering small signals or transmitting digital signals within such a noisy environment is challenging, while isolating an analog signal is an even bigger challenge. In many cases, signal isolation circuits introduce phase delays that limit system dynamic performance. Phase current sensing is particularly challenging, as this node is connected to the same circuit node as the gate driver output within the heart of the power stage (inverter block) and therefore experiences the same demands in terms of isolation voltages and switching transients. Determining the measurement signal chain (technique, signal conditioning, and ADC) to be implemented within a motor control system relies on three key factors:

1. The point or node in the system, as this determines what needs to be measured.
2. The power level of the motor and resulting sensor choice—one that is inherently isolated or not. The sensor choice has significant influence over the ADC choice, including the converter architecture, functionality, and analog input range.
3. The end application. This can drive the need for high resolution, accuracy, or speed within the sensing signal chain. Implementing sensorless control over a wide speed range, for example, demands more measurements taken more often and of higher accuracy. The end application also impacts the demand on the ADC functionality. For example, a higher channel count ADC may be required for multi-axis control.

## CURRENT AND VOLTAGE SENSORS

The most commonly used current sensors in motor control are shunt resistors, Hall effect (HE) sensors, and current transformers (CT). While shunt resistors don't provide isolation and incur losses at higher currents, they are the most linear of all the sensors, the lowest cost, and suitable for both ac and dc measurements. The signal level reductions needed to limit shunt power losses typically limit shunt applications to 50 A or less. CTs and HE sensors provide inherent isolation, allowing them to serve high current systems, but they are higher cost and result in a less accurate solution than that which can be achieved through shunt resistor usage, either due to the sensor itself having poorer initial accuracy or worse accuracy over temperature.

## MOTOR CURRENT MEASUREMENT LOCATIONS AND TOPOLOGIES

Quite apart from the sensor type, there are several motor current measurement nodes to choose from. The average dc link current can be used for control purposes, but motor winding current is used as the primary feedback variable in more advanced drives. Direct in phase winding current measurement is the ideal and used in high performance systems. However, the winding current can be measured indirectly using a shunt in each of the lower inverter legs or with a single shunt in the dc link. The advantage of these approaches is that the shunt signals are all referenced to the power common, but extraction of winding current from the dc link requires the sampling to be synchronised to the PWM switching. Direct in phase winding current measurements can be taken with any of the above current sensing techniques, but the shunt resistor signals must be isolated. A high common-mode amplifier can provide functional isolation but human safety isolation must be provided by an isolated amplifier or isolated modulator.

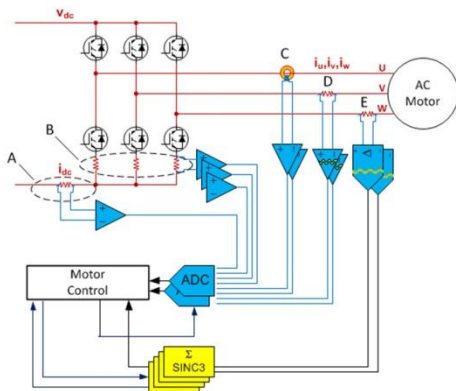


Figure 4. Isolated and Nonisolated Motor Current Feedback

Figure 4 illustrates the various current feedback options described above. While only one of these options is required for control feedback, the dc link current signal may be used as a backup signal for protection.

As already described, the system power and ground partitioning will determine what classification of isolation is required and therefore which feedback options are suitable. The system target performance will also influence the sensor choice or measurement technique. There are many configurations which may be realized spanning the performance spectrum.

## LOWER PERFORMANCE EXAMPLE: POWER STAGE AND CONTROL STAGE ON COMMON POTENTIAL, SENSING OPTION A OR B

Using leg shunts is one of the most economical techniques to measure motor current. In this example, where the power stage shares the same potential as the control stage, there is

no common mode to be dealt with and the outputs from option A or B can connect directly to the signal conditioning circuitry and ADC. This type of topology would generally be found in a low power and low performance system with the ADC embedded in the microprocessor.

## HIGHER PERFORMANCE EXAMPLE: CONTROL STAGE CONNECTED TO EARTH, SENSING OPTION C, D, OR E

In this example, human safety isolation is required. Sensing options C, D, and E are all possible. Option E provides the highest quality current feedback of all three options and, being a higher performance system, it is likely that there is an FPGA or other form of processing in the system that can provide the digital filter for the isolated modulator signal. The ADC choice for option C, the isolated sensor (likely closed loop HE), would traditionally be discrete to achieve higher performance than that possible with embedded ADC offerings to date. Option D is an isolated amplifier in this configuration, vs. a common-mode amplifier, as safety isolation is required. An isolated amplifier will limit performance, and so an embedded ADC solution may suffice. This will provide the lowest fidelity current feedback compared to options C or E, and while an embedded ADC may be perceived as “free” and the isolated amplifier potentially “cheap,” the implementation usually requires additional components for offset compensation and level shifting for ADC input range matching, increasing the overall signal chain cost.

There are many topologies that can be used in motor control design to sense motor current with many factors to consider such as cost, power level, and performance level. A key objective for most system designers is to improve the current sense feedback in order to improve efficiency within their cost targets. For higher end applications, current feedback is critical to other system performance measures such as dynamic response, acoustic noise, or torque ripple, not just efficiency. It is evident that there is a continuum of performance running from low to high across the various topologies available and this is coarsely mapped out in Figure 5 illustrating both lower power and higher power options.

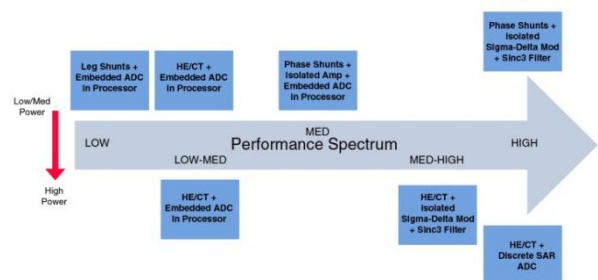


Figure 5. Current Sensing Topologies Performance Spectrum

## MOTOR CONTROL SYSTEM DESIGNER OBJECTIVES, NEEDS, AND RESULTING TRENDS: MIGRATION FROM HE SENSORS TO SHUNT RESISTORS

Shunt resistors coupled with isolated  $\Sigma$ - $\Delta$  modulators provide the highest quality current feedback where the current level is low enough for shunt usage. There is a significant trend for system designers to migrate from HE sensors to shunt resistors, with an additional trend to move to the isolated modulator approach vs. an isolated amplifier approach. The sensor change alone results in a lower bill of materials (BOM) and PCB insertion costs and improved sensor accuracy. The shunt resistor is not sensitive to magnetic fields or mechanical vibration. Quite often, system designers replacing HE sensors with shunt resistors may opt for an isolated amplifier and continue using the ADC previously used in the HE sensor based design to limit the level of change in the signal chain. However, as already noted, the performance will be limited by that of the isolated amplifier regardless of the ADC performance.

Further replacing the isolated amplifier and ADC with an isolated  $\Sigma$ - $\Delta$  modulator will eliminate the performance bottleneck and greatly improve the design typically taking it from a 9 to 10-bit quality feedback to a 12-bit level. Analog over current protection (OCP) circuitry can also potentially be eliminated, as the digital filter required to process the  $\Sigma$ - $\Delta$  modulator output can also be configured to implement a fast OCP loop. Therefore, any BOM analysis should include not only the isolated amplifier, the original ADC, and the signal conditioning between these, but also OCP devices that may be eliminated. The [AD7401A](#) isolated  $\Sigma$ - $\Delta$  modulator, based on Analog Devices iCoupler® technology, has been an ideal product choice in the uptake of this trend with a differential input range of  $\pm 250$  mV ( $\pm 320$  mV full scale commonly used for OCP), ideally suited to resistive shunt measurements. The analog input is continuously sampled by the analog modulator and the input information is contained in the digital output stream as a density of ones with a data rate up to 20 MHz. The original information can be reconstructed with an appropriate digital filter, commonly a Sinc<sup>3</sup> filter for precision current measurements. As conversion performance can be traded off vs. bandwidth, or filter group delay, a coarser, faster filter can provide fast response OCP in the order of 2  $\mu$ s, ideally suited to IGBT protection.

### DEMAND TO REDUCE SHUNT RESISTOR SIZES

From a signal measurement aspect there are some key challenges associated with the shunt resistor selection as there is a trade-off between sensitivity and power dissipation. A large resistor value will ensure the full range, or as much as possible of the analog input range, of the  $\Sigma$ - $\Delta$  modulator will be used, thus maximizing dynamic range. However, a large resistor value also results in a voltage drop

and a reduction in the efficiency due to the  $I^2 \times R$  loss of the resistor. Nonlinearity through self heating effects can also be a challenge using larger resistors. As a result, system designers are faced with making trade-offs and further exacerbating this is a common need to select a shunt size that will service many models and motors at different current levels. Maintaining dynamic range is also challenging in the face of peak currents that can be several times the rated current of the motor and the need to reliably capture both. The ability to control peak currents at system turn on varies greatly depending on the design, varying from tight control of, say, 30% above nominal, to as much as a factor of 10 times the nominal current. Peak currents also result from acceleration and load or torque change. However, in general it is common to see the peak current in a system to be in the region of 4 times the nominal current in drive designs.

In the face of these challenges, system designers are looking for superior  $\Sigma$ - $\Delta$  modulators with wider dynamic range, or improved signal to noise and distortion ratio (SINAD). Isolated  $\Sigma$ - $\Delta$  modulator offerings to date have provided 16-bit resolution with up to 12-bit effective number of bits (ENOB) guaranteed performance.

$$SINAD = (6.02 N + 1.76) \text{ dB where } N = \text{ENOB}$$

Following the shift to shunt resistor usage in lower power drives, motor drive manufacturers are also looking to increase the power rating of drives that can make use of this topology both for performance and cost reasons. This is only possible though the use of much smaller shunt resistors, which requires the advent of a much higher performance modulator core to resolve the diminished signal amplitude.

System designers, particularly servo designers, are also constantly looking to improve system response through reduced analog to digital conversion time, or reduced group delay through the digital filter associated with the isolated  $\Sigma$ - $\Delta$  modulator and shunt resistor topology. As already noted, conversion performance can be traded off vs. bandwidth, or filter group delay. A coarser, faster filter can provide a faster response, but at the expense of performance. System designers analyze the effects of filter length or decimation ratio and then make trade offs according to their end application needs. Increasing the clock rate of the modulator helps, but many designers are already operating at the maximum clock rate of 20 MHz that the AD7401A accepts. One of the drawbacks with increasing the clock rate is potential radiation and interference (EMI) effects. A higher performance modulator at the same clock rate would improve the group delay vs. performance trade off, allowing faster response time with less impact on performance.



**INDUSTRY'S HIGHEST PERFORMANCE ISOLATED  $\Sigma$ - $\Delta$  MODULATOR**

It is evident that a higher performance isolated  $\Sigma$ - $\Delta$  modulator would support several needs and trends within industrial motor control designs and improve the power efficiency of motor drives through shunt resistor size reduction; improved sensorless control schemes; enabling the control of high efficiency interior permanent magnet motors (IPM). The [AD7403](#) from Analog Devices is the next generation product to the AD7401A, providing much wider dynamic range at the same external clock rate of 20 MHz. This allows more flexible shunt size selection, optimizing drive to motor matching, improving nominal and peak current measurement, reducing the impact of a single shunt size for a range of motor models, and allowing for shunt resistor usage in place of HE sensors at higher current levels. Dynamic response can also be improved through reduced measurement latency. The AD7403 also features an isolation scheme with a higher continuous working voltage ( $V_{IORM}$ ) than the previous generation [AD7400A](#) and AD7401A, which can also contribute to higher system efficiency through the use of higher dc bus voltages and thus lower motor currents.

**BROADER SYSTEM SOLUTION INCLUDING THE ADSP-CM40x MIXED SIGNAL CONTROL PROCESSOR**

As already noted, the implementation of a  $\Sigma$ - $\Delta$  modulator requires a digital filter in the system. This is traditionally implemented with an FPGA or digital ASIC. The advent of the [ADSP-CM408F](#) mixed-signal control processor, which includes hardware Sinc<sup>3</sup> filters to which the AD740x series of isolated  $\Sigma$ - $\Delta$  modulators can directly connect, is likely to lead to an increased rate of adoption of the resistive shunt current sensing technique coupled with isolated  $\Sigma$ - $\Delta$  modulators. As outlined, this technique was traditionally considered expensive as a result of greater system complexity in the digital domain and associated (FPGA) cost. The ADSP-CM408F is a cost effective solution and should enable many designers to consider resistive shunt current sensing who were previously constrained by their cost targets.

**RESOURCES**

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