# **Motor Control**

# Overview

# Introduction

Motor control design for industrial applications requires attention to both superior performance and ruggedness. Maxim's feature integration and superior specifications enhance motor controller equipment precision while improving robustness in harsh industrial environments.

Motor controllers either control variable power supplies to the motor or to electronic switches between the power supply and the motor. These switches are precisely timed to open and close to make the motor rotate most effectively. The timing is often governed by complex mathematical equations based on motor architecture and electromagnetic theory. Depending on the application, a motor controller can be as simple as a variablevoltage generator, a pulsed-DC voltage source, or a complex signal generator requiring sophisticated digital signal processing algorithms to generate the correct timing. For large motors, those in the multihorsepower range with multiple power phases, precise control is essential. At a minimum, the wrong timing can result in extreme power use. In the worst case, wrong timing can destroy the motor and the installation itself.

Many electric motors have maximum torgue at zero RPM, so these large motors must be soft-started. To reduce maintenance to a minimum, the mechanical mechanisms (clutches) that traditionally provided this softstart capability are rapidly being replaced by electronic soft-starters or variable frequency drives (VFDs). In some applications motors must supply both forward and reverse tension to the load; optimally, braking energy from overhauling loads is fed back into the AC line using regenerative VFDs instead of being wasted as heat in large braking resistors or in highmaintenance mechanical brakes.

Motor control is a very significant portion of the Control and Automation market. According to U.S. Department of Energy, motor driven equipment accounts for 64% of the electricity consumed by U.S. industries. Furthermore, electric motors consume about 45% of the world's electricity according to the International Energy Agency (IEA) report of May 2011 on global energy consumption by electric motor driven systems. By comparison, lighting is a distant second consuming 19%. With the cost of energy rising steadily, plant operators look for ways to reduce energy consumption while maintaining throughput. Furthermore, with the availability of reasonably priced and highly capable motor controllers for all types of motors, plant engineers are free to choose motor types that are less expensive, more efficient, and require less maintenance.

To put the energy savings opportunity in perspective, compare motor power consumption vs. speed when driving fans and centrifugal pumps. The torque needed rises with speed, resulting in power draw that is proportional to the cube of the speed! In other words, reducing the speed to one-half of full speed drops the power to one-eighth of full power. Even dropping the speed to 75% of full speed drops the power consumption to 42% of full power (0.75 cubed = 0.42). It is clear that *significant* savings in energy use can be realized by even small reductions in speed. This fact, in turn, justifies the use of VFDs in applications that can tolerate the speed reduction. Of course, speed reduction equates to performing the work more slowly, which, in some cases, directly impacts throughput. Nonetheless, there are numerous applications where motors do not need to run at full speed to accomplish the work quickly enough. Pumping out a tank of fluid may not need to be done as fast as possible. Venting a room may need a full-speed fan at first, but once the air is moving a slower speed may suffice. The EIA report (May 2011) states that it is feasible and cost effective to save 20% to 30% of total motor power consumption worldwide.

Certainly adding variable-speed controllers adds cost to the installation; however, the forecasted energy savings will soon offset those initial expenses. The return-on-investment calculations are often straightforward.

#### Interfacing to the Motor Controller

A very important aspect of every motor controller in the industrial control and automation setting is the communications interface between the factory control system and the individual motor controller. All the block diagrams in the individual motor controller sections show a control panel that provides a direct user interface at the controller and a standard separately wired communications interface that connects to the fieldbus. The fieldbus ultimately runs back to a PLC (programmable logic controller) that sends commands to the motor controller such as motor start, motor acceleration, speed adjustment, motor stop, etc. An additional option exists: powerline communications (PLC, not to be confused with programmable logic controller). This technology gives the option of sharing command and control connections with power connections between the PLC (programmable logic controller) and the motor controller.

#### Motor Types Brushed DC Motors (BDCs)

Brushed DC (BDC) motors are among the first motor types put to practical use and they are still popular where low initial cost is required. These motors have a wound rotor armature and either a permanent magnet stator or field wound stator. Brushes slide across the segments of the commutator on the rotor to switch the DC power source to the appropriate windings on the rotor.

BDC motors have their place for two important reasons: low initial cost and ruggedness, because no electronics are needed inside the motor. Because the motors suffer from wear of the brushes, brush springs, and commutators, they require high maintenance in intensiveuse applications. Sparking also occurs between the brushes and the commutator as a part of normal motor operation. This, in turn, creates EMI/RFI and small amounts of ozone. Where system cost is a priority, BDC motors are a lowcost solution. While their efficiency is generally lower than brushless DC (BLDC) motors, they approach equality under high-load conditions.

#### **Controllers for BDC Motors**

The only variable available to control the speed of a BDC motor is the supply voltage. The voltage can be varied or a fixed voltage can be pulsed with variable duty cycle. For high efficiency in a variable voltage approach, a switchmode power supply is required. Most designers are abandoning linear voltage regulation because of its inherently low efficiency. One way to realize a variable-voltage power supply from any switch-mode voltage regulator is to inject or extract current into or out of its feedback node using a current sink/ source DAC. See **Figure 1**. When the

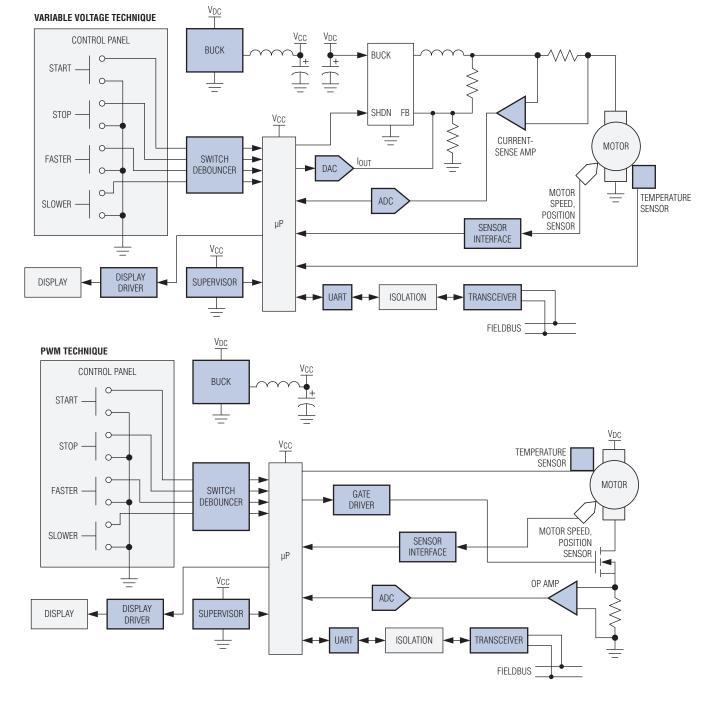


Figure 1. Two control techniques for BDC motors. The upper diagram shows a variable voltage technique that is high efficiency due to the switching power supply. The lower diagram shows the PWM technique that can be lower cost if the motor is rated for the full supply voltage.

user adjusts the speed control or when the microcontroller receives a command through the electronic interface, the microcontroller then instructs the current sink/source DAC (e.g., DS4432) to change its output current value. This forces the regulator to change the output voltage to the motor up or down, respectively, to keep the feedback pin's voltage constant.

Alternatively, if the motor can handle the high-DC voltage, one can convert the input control to a pulse-widthmodulated (PWM) duty cycle applied to a power switch between the power supply and the motor. By varying the duty cycle, the average power to the motor is adjusted, as is its output power and speed. If constant speed is needed under a varying load, then motor speed detection is needed. This motor

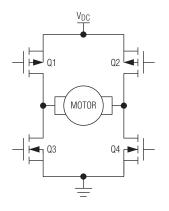


Figure 2. H-bridge for driving a BDC motor in both directions. When Q1 and Q4 are on, the motor moves one direction. When Q2 and Q3 are on, the motor moves in the opposite direction.

speed signal (usually a pulse frequency proportional to the motor rotation rate) must be fed into a controller that will respond by either adjusting the motor voltage or the PWM duty cycle. With sufficient switching frequency, the inductance of the motor windings act as a lowpass filter that keeps the motor current close to constant with only minor ripple, thus producing low torque ripple.

To reverse the direction of the BDC motor, current must flow through the motor in the opposite direction. This can be accomplished using power MOSFETs or IGBTs in an H-bridge configuration (**Figure 2**). These MOSFETs can be either voltage controlled or PWM controlled for speed control.

#### **Brushless DC (BLDC) Motors**

A BLDC motor spins the magnets instead of the windings—the inverse of a BDC motor. This has advantages and disadvantages. A BLDC motor has neither commutator nor brushes, so it requires less maintenance than a BDC motor. The BLDC motor's rotor can take different forms, but all are permanent magnets.

The armature is fixed and holds the stator windings; the rotor carries the magnets and can either be an "inrunner" or an "outrunner." Inrunners have the rotor inside the stator and outrunners have the rotor outside the stator (**Figure 3**). Either approach eliminates the problem of connecting the power source to a

rotating part through a commutator. The brushes and mechanical commutator are replaced by electronic commutation of the stator windings. This increases motor life significantly. The initial cost of a BLDC motor is higher than an equivalent BDC motor, although the cost of permanent magnets has decreased significantly over the past years. With precise commutation and rotor position sensing, efficiency is generally higher than equivalent BDC motors. They also produce more torque per unit weight. Another significant advantage for industrial applications is that since there are no brushes, there are no sparks generated, so the BLDC motors can be used in explosive environments.

Due to their higher efficiency over a wide range of speeds and loads, BLDC motors are seeing wider use in heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems.



Figure 3. Disassembled outrunner BLDC motor. Fixed armature carries the stator windings. The rotor carries the permanent magnets.

#### **Controllers for BLDC Motors**

Since the commutation in a BLDC motor (Figure 4) is electronic, some means is required for detecting rotor position relative to the stationary armature. Typical solutions for this are Hall-effect sensors and rotary encoders such as optical encoders, resolvers, or rotary variable differential transformers (RVDTs). More designs are using sensorless approaches where stator coil back EMF variation is sensed, which indicates rotor position. This information is typically sent to a microprocessor to determine power FET drive timing. Various user interfaces allow softstarting, acceleration control, speed control, and response to locked rotor.

#### **Stepper Motors**

Stepper motors are really more like rotary positioners than motors. They are usually smaller motors with many poles used for precise positioning applications (Figure 5). They are often driven "open loop," meaning there is no position detection. Their position is assumed to follow the step commands exactly. Loss of step position can occur, however, so some mechanism must be provided to indicate slippage and to reset proper positioning. At low drive rates, they come to a complete stop between each step. Many drive waveforms are possible, the simplest has each winding energized one at a time. Other variations are possible where overlap in energization

occurs between adjacent windings to provide smaller steps. Microstepping is achieved with sinusoidal, overlapping current waveforms that give very smooth and quiet rotation.



Figure 5. Stepper motor (windings removed) showing multitoothed rotor and stator design for fine stepping.

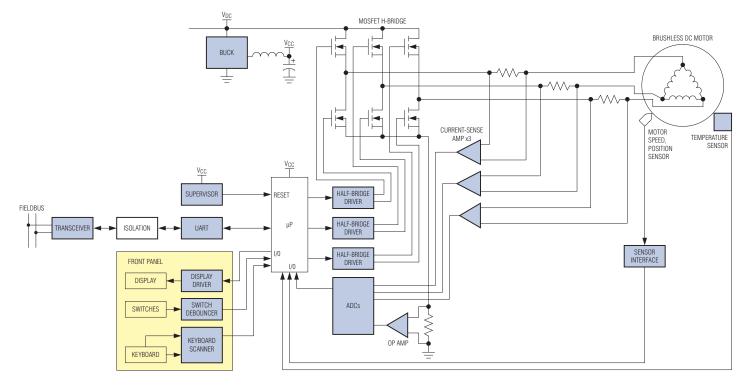


Figure 4. Controller for BLDC motor.

#### **Controllers for Stepper Motors**

Stepper motors are constant power motors if driven with a constant supply voltage. As speed increases, torque decreases. This happens because of the limitation on current ramp rates in the windings due to their inductance. Maximum torgue is realized at zero speed. So to increase torgue at higher speeds, high-voltage drivers with current limiting are sometimes used (Figure 6). These are called "chopper drives," and are designed to generate a nearly constant current in each winding rather than simply switching a constant voltage. On each step, a very high voltage is applied to the winding. When the current limit is reached, the voltage is turned off or "chopped." At this point the winding current starts ramping down to a lower limit where the voltage is again turned on, keeping the winding current relatively constant

for a particular step position. The additional electronics to sense winding currents and to control the switching adds some cost and complexity, but it allows stepper motors to be driven with high torque at high speed.

Microprocessors are commonly incorporated in stepper motor drivers to provide the controls needed. Sophisticated control capability is common for stepper motors since they are often employed in machines that require fast precision movements, such as in robotics. Acceleration/deceleration profiles, holding torque, and other parameters are often provided for.

#### Switched Reluctance Motors (SRMs)

Switched reluctance motors (SRMs) are a form of stepper motor, but are usually much larger and have fewer poles than the traditional stepper motor. The key to these motors is that the rotor is made of only ferromagnetic material and has no windings. It is a very reliable, low-maintenance motor with high power density at low cost, all of which come at the expense of more complex electronic controls.

Opposing stator poles are energized in sequence and the rotor poles closest to the energized stator poles become magnetized and are attracted to them, reducing magnetic reluctance when brought into alignment. Before full alignment is achieved, the next phase is energized to keep the motor turning. There is no need for any transfer of electrical power to the rotor so there are no brushes, commutators, or slip rings. With electrical commutation there are no sparks so these motors can be used in explosive environments. They are also good for holding a load in a stationary position for long periods of time.

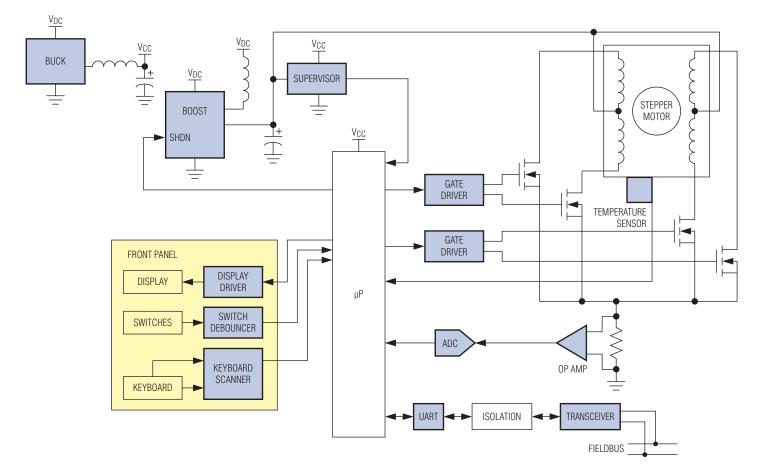


Figure 6. Controller for stepper motor. The boost regulator and the current sense per phase allow current to ramp quickly in each pole of the motor. Motor response is fast. When the maximum current per phase is reached, the boost regulator is shut down until the minimum current per phase is reached again. The cycle is repeated until the next step is made.

#### **Controllers for SRMs**

SRMs are similar to stepper motors because they need power switched to the proper windings at the appropriate times. The most common configuration is similar to an H-bridge, but differs somewhat. The driver is called an N+1 switch and diode asymmetric bridge converter (**Figure 7**). It allows each phase of a 3-phase motor to be energized by the top FET and the appropriate bottom FET, which are both turned on simultaneously (**Figure 8**). The current is allowed to ramp up to a limit, at which point the top FET is turned off. This is the freewheeling mode, where the winding inductance keeps the current

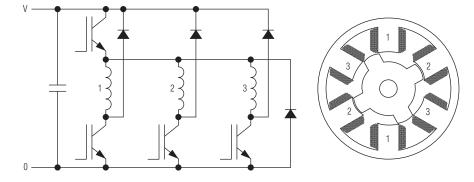


Figure 7. "N+1 switch and diode" asymmetric bridge for driving SRMs. The control circuitry needed for the IGBTs shown is shown in Figure 8.

relatively constant, ramping down only very slowly with the bottom diode closing the loop around the winding. Then to discharge the phase quickly in preparation for the next step, the bottom FET is also turned off. The voltage across the winding is now clamped to the opposite polarity by the top and bottom diodes. This causes the current to ramp down at about the same rate that it ramped up, except for the effect of two additional diode drops making it ramp down slightly faster. This configuration allows each phase to be switched on and off guickly, especially with a highvoltage supply, allowing for high-speed motor operation at high torque. Figure 8 shows only a single current-sense amp sensing the current on the high-side FET. This is only adequate for simple control systems. Complete control also requires current sensing on each low-side FET.

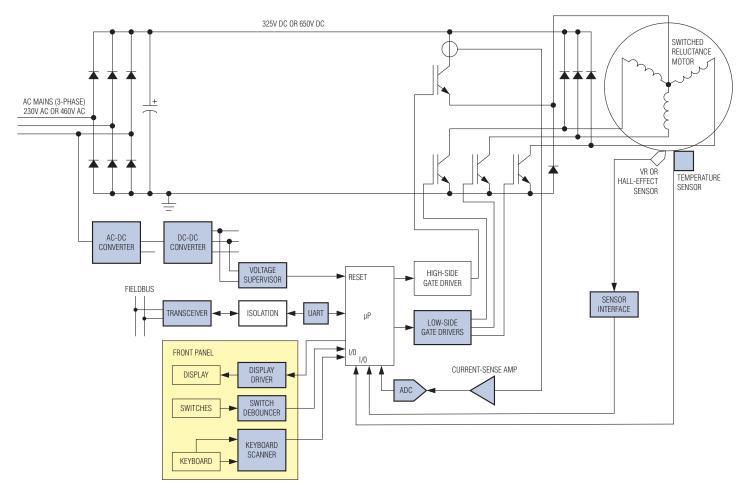


Figure 8. Controller for a switched reluctance motor.

#### **AC Induction Motor**

The AC induction motor (**Figure 9**) is the workhorse motor for many industrial applications such as those for driving pumps, blowers, conveyors, cranes, etc. It is one of the simplest and most reliable motor designs and can range in size from a few watts to many kilowatts. The induction motor is an asynchronous motor and is basically an AC transformer with a rotating shorted secondary. The primary winding (stator) is connected to the power source and



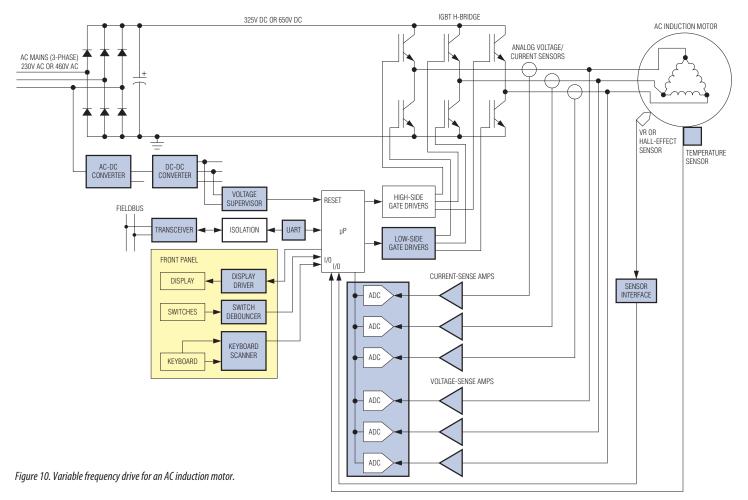
Figure 9. An AC induction motor.

the secondary winding (rotor) carries the induced secondary current creating a magnetic field. Torque is produced as the rotor field tries to align itself with the applied rotating stator field. No slip rings or commutators are needed since no source power is physically connected to the rotor. The most common designs have three stator windings and are driven from 3-phase AC sources. Although direct connection to AC mains is therefore possible, in most applications, induction motors require some form of soft-starter or VFD.

Induction motors "slip" under load. The amount of slip is directly proportional to the torque required to drive the load. Under no-load conditions, no torque is produced and the rotational speed is almost exactly the driving frequency divided by the number of poles in the stator. These motors are easily speed and torque controlled by varying the drive frequency and voltage, respectively. If constant speed is needed, VFDs can use position- or speed-detection feedback to increase the drive frequency as needed to keep the motor speed constant under varying loads.

#### **Controllers for AC Induction Motors**

AC induction motors operate with the least torque ripple when the phase current is sinusoidal. Due to the inductance of the windings, the phase can be PWM driven from a fixed DC supply to achieve this current waveform. The two most common approaches to induction motor drive include "vector control" and "direct torque control." These techniques are beyond the scope of this document, but information is readily available. Suffice it to say that to fully implement these control techniques, a fairly powerful processor or DSP is required, but the benefits are many. The result is a VFD (Figure 10)



that provides complete control capability over motor soft-starting, acceleration, torque, speed maintenance, deceleration, and holding torque.

#### **Synchronous Motors**

A synchronous motor runs synchronously with the AC excitation it receives. Various configurations are possible. One approach applies the AC line to the stator windings around the frame while a DC excitation is applied through slip rings to the rotor. In many synchronous motors the rotor has permanent magnets instead of DC-excited windings. Highspeed synchronous motors are used in machining applications where the cutter speed must be maintained at precisely fixed rates or the machined-surface finish will show signs of speed variation.

When driven mechanically, synchronous motors will produce electricity, becoming alternators. They are used extensively in power plants to generate grid power.

DC-excited synchronous motors can also be used in power plants and large factories to correct the power factor by being run under no load in parallel with the large loads. As the DC excitation of the rotor is modified, it produces either a leading or lagging power factor to cancel the nonunity power factor of the load. In this application they are called synchronous condensers.

#### **Controllers for AC Synchronous Motors**

Various control methods exist for AC synchronous motors. The motors' stator windings can be driven with variable-frequency AC signals from a VFD, thereby providing soft-starting and exacting speed control. If a low frequency is not first applied to a stopped synchronous motor, it will not self-start. It must be given a chance to "pull in" to synchronization. Some synchronous motors allow the rotor windings to be shorted, temporarily converting it to an induction motor while it starts. Then once it is close to synchronous speed, the short is opened and it becomes synchronous.



Figure 11. Maglev train driven by a linear motor.

If the rotor uses DC excitation, its voltage can vary with a high-efficiency switching power supply and voltage control.

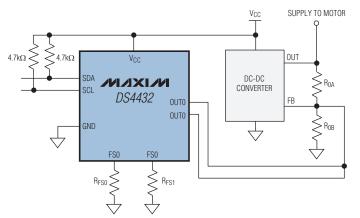
#### **Linear Motors**

Linear motors are effectively motors that have been unrolled and laid out flat. The moving part is usually called the forcer and is connected to the external power source while the rails are lined with permanent magnets. The opposite configuration is also used. Everything from maglev trains (Figure 11) to rail guns are based on this principle. Very precise machine positioning systems use these motors for cutting large objects with high accuracy. Linear motors include linear induction motors (LIMs) and linear synchronous motors (LSMs). Controllers for linear motors are guite varied due to the wide range of applications for them. Nonetheless, they share similarities with VFDs.

# Sink/Source Current DAC Adjusts Power-Supply Output Voltage to Vary Supply to Motors

DS4432

The DS4432 contains two I<sup>2</sup>C programmable current DACs that are each capable of sinking and sourcing current up to 200 $\mu$ A. Each DAC output has 127 sink and 127 source settings that are programmable using the I<sup>2</sup>C interface. The current DAC outputs power up in a high-impedance state. Full-scale range for each DAC is set by external resistors providing highly scalable outputs. Fine and course granularity can be achieved by combining the two outputs when set for different ranges.



*Typical operating circuit of the DS4432.* 

#### **Benefits**

- Simplicity of DC motor speed control via digital interface
- Easy design reuse due to highly scalable outputs
- Dual outputs with individual range settings provide course and fine motor speed control

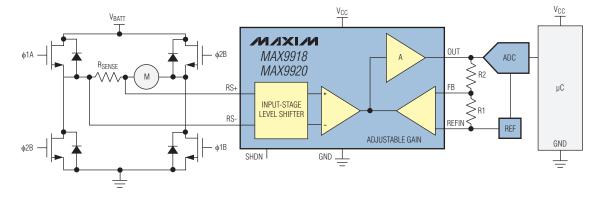
# Precise Current Measurements Ensure Better Motor Control

MAX9918/MAX9919/MAX9920

The MAX9918/MAX9919/MAX9920 are current-sense amplifiers with a -20V to +75V input range. The devices provide unidirectional/bidirectional current sensing in very harsh environments where the input common-mode range can become negative. Uni/bidirectional current sensing measures charge and discharge current in a system. The single-supply operation shortens the design time and reduces the cost of the overall system.

#### **Benefits**

- Provide reliable operation in harsh motor control environments
  - 400µV (max) input offset voltage (V<sub>OS</sub>)
  - -20V to +75V common-mode voltage range provides reliability for measuring the current of inductive loads
  - -40°C to +125°C automotive temperature range
- Integrated functionality reduces system cost and shortens design cycle
- Uni/bidirectional current sensing
- Single-supply operation (4.5V to 5.5V) eliminates the need for a second supply
- 400µV (max) input offset voltage (V<sub>OS</sub>)
- 0.6% (max) gain accuracy error



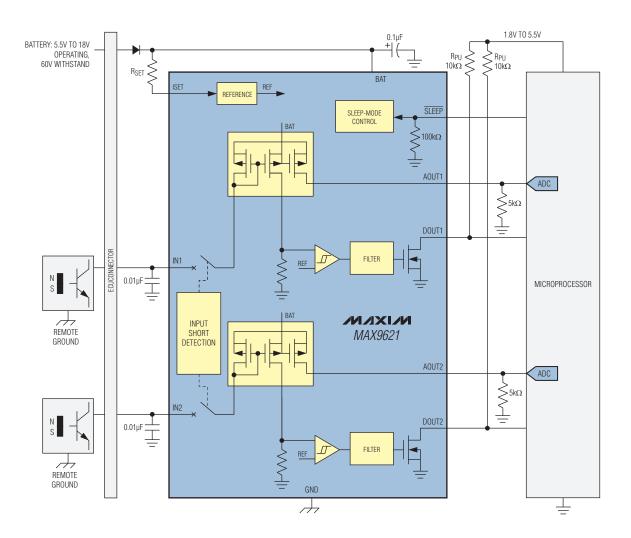
The MAX9918/MAX9920 current-sense amplifiers provide precise uni/bidirectional current sensing in very harsh environments.

### Highly Accurate, Reliable Monitoring of Motor Speed and Position with a Sensor Interface MAX9621

The MAX9621 is a dual, 2-wire Hall-effect sensor interface with analog and digital outputs. This device enables a microprocessor to monitor the status of two Hall-effect sensors, either through the analog output by mirroring the sensor current for linear information, or through the filtered digital output. The input current threshold can be adjusted to the magnetic field. The MAX9621 provides a supply current to two 2-wire Hall-effect sensors and operates in the 5.5V to 18V voltage range. The high-side current-sense architecture eliminates the need for a ground-return wire without introducing ground shift. This feature saves 50% of the wiring cost.

#### Benefits

- Integrated functionality eases motor control design, reduces system cost
  - Select the analog or digital output to monitor the Hall-effect sensor's condition
  - High-side current-sense architecture eliminates the need for a groundreturn wire and saves 50% of the wiring cost
- Reliable operation in a harsh environment
  - Protects against up to 60V supply voltage transients
  - Detects a short-to-ground fault condition to protect the system



Functional diagram of the MAX9621 Hall-effect sensor interface.

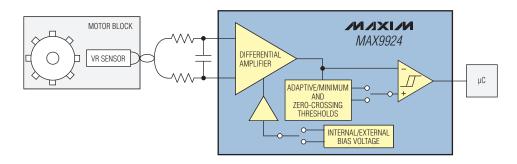
# Improve Performance and Reliability in Motor Applications with a Differential VR Sensor Interface

MAX9924–MAX9927

The MAX9924–MAX9927 VR, or magnetic coil, sensor interface devices are ideal for sensing the position and speed of motor shafts, camshafts, transmission shafts, and other rotating wheel shafts. These devices integrate a precision amplifier and comparator with selectable adaptive peak threshold and zero-crossing circuit blocks that generate robust output pulses, even in the presence of substantial system noise or extremely weak VR signals. The MAX9924–MAX9927 interface to both single-ended and differential-ended VR sensors.

#### **Benefits**

- High integration provides accurate phase information for precise sensing of rotor position
  - Differential input stage provides enhanced noise immunity
  - Precision amplifier and comparator allow small-signal detection
  - Zero-crossing detection provides accurate phase information



Simplified block diagram of the MAX9924 VR sensor interface to a motor.

### Resolve Very Fine Motor Adjustments and Operate Higher Accuracy Systems with Simultaneous-Sampling ADCs

MAX11044/MAX11045/MAX11046 MAX11047/MAX11048/MAX11049

The MAX11044–MAX11049 ADCs are an ideal fit for motor control applications that require a wide dynamic range. With a 93dB signal-to-noise ratio (SNR), these ADCs detect very fine changes to motor currents and voltages, which enables a more precise reading of motor performance over time. The MAX11044/MAX11045/ MAX11046 simultaneously sample four, six, or eight analog inputs, respectively. All ADCs operate from a single 5V supply. The MAX11044–MAX11046 ADCs measure ±5V analog inputs, and the MAX11047–MAX11049 measure 0 to 5V. These ADCs also include analog input clamps that eliminate an external buffer on each channel.

#### DSP-BASED DIGITAL MAX11046 PROCESSING ENGINE 16-BIT ADC IGBT CURRENT DRIVERS 16-BIT ADC 16-BIT ADC 16-BIT ADC 16-BIT ADC PHASE1 PHASE3 IPHASE2 THREE-PHASE FLECTRIC MOTOR POSITION ENCODEF

The MAX11046 ADC simultaneously samples up to 8 analog-input channels.

#### Benefits

- Industry-leading dynamic range allows early detection of error signals
  - 93dB SNR and -105dB THD
- Simultaneous sampling eliminates phase-adjust firmware requirements
  - 8-, 6-, or 4-channel ADC options
  - Lower system cost by as much as 15% over competing simultaneoussampling ADCs
  - High-impedance input saves costly precision op amp
  - Bipolar input eliminates level shifter
  - Single 5V voltage supply
  - 20mA surge protection
- Eliminate external protection
  components, saving space and cost
  - Integrated analog-input clamps and small 8mm x 8mm TQFN package provide the highest density per channel

# **Recommended Solutions**

| Part                             | Description  | Features   | Benefits   |
|----------------------------------|--|--|--|
| AC-DC and DC-DC Converters a     | nd Controllers   |  |  |
| MAX17499/500                     | Isolated/nonisolated current-mode<br>PWM controllers ideal for flyback/<br>forward topologies  | 85V AC to 265V AC universal offline<br>input voltage range (MAX17500),<br>9.5V DC to 24V DC input voltage<br>range (MAX17499), programmable<br>switching frequency up to 625kHz,<br>1.5% reference accuracy                          | Primary-side regulation eliminates<br>optocouplers, allowing low-cost<br>isolated supplies.  |
| MAX5069                          | Isolated/nonisolated current<br>mode PWM controller with dual<br>FET drivers ideal for push-pull and<br>half/full-bridge power supplies        | 85V AC to 265V AC universal<br>offline input voltage range<br>(MAX5069A/B), 10.8V DC to<br>24V DC input voltage range<br>(MAX5069C/D), programmable<br>switching frequency up to 2.5MHz,<br>programmable UVLO and UVLO<br>hysteresis | Minimizes footprint due to wide<br>range programmable switching<br>frequency; programmable<br>UVLO/hysteresis ensures proper<br>operation during brownout<br>conditions. |
| MAX15062*                        | High-voltage synchronous, micro<br>buck regulator  | 4V to 36V input voltage range,<br>fixed 700kHz switching frequency,<br>integrated high-side and low-side<br>FETs, internal compensation  | Reduces total solution size and cost with high integration and small package.  |
| ADCs                             |  |  |  |
| MAX11044/45/46<br>MAX11047/48/49 | 16-bit, 4-/6-/8-channel,<br>simultaneous-sampling SAR ADCs   | 93dB SNR: -105dB THD; 0 to 5V<br>or $\pm$ 5V inputs; parallel interface<br>outputs, all eight data results in<br>250ksps; high-input impedance<br>(> 1M $\Omega$ )   | High-impedance input saves the cost and space of external amplifier.   |
| MAX1377/MAX1379/MAX1383          | 12-bit, dual, 1.25Msps,<br>simultaneous-sampling SAR ADCs  | 0 to 5V, 0 to 10V, or $\pm$ 10V inputs: 70dB SNR; SPI interface  | Serial interface saves cost and space on digital isolators.  |
| MAX11040K                        | 24-bit, 4-channel, simultaneous-<br>sampling, sigma-delta ADC  | 117dB SNR, 64ksps, internal<br>reference, SPI interface, 38-pin<br>TSSOP package   | Reduces motor control firmware complexity.   |
| MAX11203                         | 16-bit single-channel, ultra-low-<br>power, delta-sigma ADC  | Programmable gain, GPIO, high resolution per unit power ratio  | Eases achieving high-efficiency designs.   |
| DACs                             |  |  |  |
| DS4432                           | Dual sink/source current DAC<br>with sink and source settings<br>programmable via I <sup>2</sup> C interface;<br>range settable with resistors | 50μA to 200μA sink/source range,<br>127 sink, 127 source settings  | Provides simple and precise digital<br>speed control for a wide range of<br>DC motor control applications.   |
| Current-Sense Amplifiers         |  |  |  |
| MAX34406                         | Quad current-sense amplifier with overcurrent threshold comparators  | Unidirectional current sensing;<br>fixed gains of 25, 50, 100, and<br>200V/V; ±0.6% gain error; 2V to<br>28V common-mode range   | Wide dynamic range supports<br>wide range of motor current-<br>sensing applications.   |
| MAX9918/19/20                    | -20V to +75V input range; uni/<br>bidirectional current-sense<br>amplifiers  | 0.6% max gain error, 120kHz -3dB<br>BW, -40°C to +125°C operating<br>temperature range   | Wide dynamic range and high accuracy supports wide range of motor current-sensing applications.  |
| MAX9643                          | High-speed current-sense amplifier   | 15MHz bandwidth, -1.5V to +60V<br>input range, 50μV max V <sub>OS</sub> , -40°C to<br>+125°C operating temperature range   | Provides very fast response to<br>quickly changing currents in motor<br>control applications.  |

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| Part                           | Description   | Features  | Benefits  |
|--------------------------------|---|---|---|
| <b>Operational Amplifiers</b>  |   |   |   |
| MAX9617/18/19/20               | High efficiency, zero drift, op amps with low noise and RRIO  | 10μV (max) V <sub>OS</sub> over time and<br>temperature range of -40°C to<br>+125°C, 59μA supply current,<br>1.5MHz GBW, SC70 package                               | Allow sensing low-side motor current with high accuracy at low power consumption.   |
| MAX9943/44                     | 38V precision, single and dual op amps  | Wide 6V to 38V supply range, low<br>100µV (max) input offset voltage,<br>drives 1nF loads   | Wide operating voltage range<br>and precision performance under<br>most capacitive loads provide<br>signal processing in wide range of<br>applications. |
| Hall-Effect Sensor Interface   |   |   |   |
| MAX9621                        | Dual, 2-wire Hall-effect sensor<br>interface  | Analog and filtered digital<br>outputs, high-side current sense,<br>60V capability, detects short to<br>ground fault  | Integration eases motor control design.   |
| Temperature Sensors            |   |   |   |
| MAX31723                       | Digital thermostat with SPI/3-wire interface  | No external components, -55°C<br>to +125°C measurement range,<br>±0.5°C accuracy, configurable<br>9- to 12-bit resolution, nonvolatile<br>thermostat thresholds     | Eases processor burden by storing<br>temperature thresholds internally<br>in nonvolatile memory.  |
| MAX31855                       | Thermocouple-to-digital converter   | Cold-junction compensated; works<br>with K, J, N, T, or E types; 14-bit, SPI<br>interface; -270°C to +1800°C  | Simplifies system design while<br>providing flexibility for various<br>thermocouple types.  |
| Variable Reluctance (VR) Senso | r Interface   |   |   |
| MAX9924-MAX9927                | Reluctance (VR or magnetic coil) sensor interfaces  | Integrated precision amplifier<br>and comparator for small-signal<br>detection, flexible threshold<br>options, differential input stage,<br>zero-crossing detection | Improve performance by<br>accurately detecting position and<br>speed of motors and rotating<br>shafts.  |
| MOSFET Drivers                 |   |   |   |
| MAX15012                       | Half-bridge gate driver for high-<br>and low-side MOSFETs with 2A<br>peak source/sink current drive | UVLO, fast (35ns typ) and matched<br>(8ns max) propagation delays,<br>175V high-side MOSFET voltage<br>capability   | Prevents MOSFET damage due to<br>supply brownout; allows higher<br>frequency switching applications;<br>allows use in high voltage<br>applications.     |
| MAX15024                       | Low-side, 4A MOSFET drivers   | Single/dual operation, 16ns<br>propagation delay, high sink/<br>source current, 1.9W thermally<br>enhanced TDFN package   | Shrinks designs with small<br>package and allows fast switching<br>with tightly matched propagation<br>delays.  |

(Continued on following page)

| Part                   | Description   | Features   | Benefits   |
|------------------------|---|--|--|
| Interface Transceivers |   |  |  |
| MAX13448E              | Fault-protected RS-485 transceiver                            | ±80V fault protected, full-duplex operation, 3V to 5.5V operation  | Makes equipment more robust<br>and tolerant of misconnection<br>faults.                            |
| MAX14840E              | High-speed RS-485 transceiver                                 | 40Mbps data rates, ±35kV (HBM)<br>ESD tolerance, 3.3V, +125°C<br>operating temperature, small 3mm<br>x 3mm TQFN package                              | High receiver sensitivity and hysteresis extend cable lengths in harsh motor control environments. |
| MAX14770E              | PROFIBUS transceiver  | ±35kV (HBM) ESD protection,<br>-40°C to +125°C temperature<br>range, small 3mm x 3mm TQFN<br>package   | Industry's highest ESD protection makes motor control more robust.                                 |
| MAX13171E/3E/5E        | Multiprotocol data interface<br>chipset                       | Complete RS-232 and related<br>protocols equipment interface<br>solution, up to 40Mbps, true<br>fail-safe receivers, ±15kV ESD<br>protection         | Enable flexible interfaces with pin-<br>selectable protocols.                                      |
| MAX13051               | CAN transceiver   | ±80V fault protection, autobaud,<br>ISO 11898 compatible, up to<br>1Mbps, -40°C to +125°C operation  | Provides robust industrial strength CAN interface solution.  |
| Voltage Supervisors    |   |  |  |
| MAX16052/3             | High-voltage supervisor                                       | Adjustable voltage thresholds and timeout; V <sub>CC</sub> to 16V and open-<br>drain output to 28V   | Ease supervisory designs for<br>industrial applications with high-<br>voltage capability.          |
| MAX6495                | 72V overvoltage protector                                     | Protects against transients up to 72V, small 6-pin TDFN-EP package   | Increases system reliability by<br>preventing component damage<br>from high-voltage transients.    |
| Control Interfaces     |   |  |  |
| MAX6816/17/18          | Single, dual, octal switch debouncer                          | ±15kV ESD (HBM) protection   | Assure high reliability, clean<br>pushbutton signal from motor<br>control panels.                  |
| MAX7370                | Key-switch controller plus LED backlight drive with dimming   | Up to 64-key, separate press/<br>release codes, ±14kV Air Gap ESD,<br>LED drive with PWM dimming<br>control and blink, optional GPIO                 | Enables high reliability keyboard scanning and display illumination in one IC.                     |
| MAX16054               | Pushbutton on/off controller with debounce and ESD protection | Handles ±25V input levels,<br>±15kV ESD, deterministic output<br>on power-up, no external<br>components  | Enables simple, robust control panel interface in small SOT23 package.                             |
| MAX6971                | 16-port, 36V constant current LED driver                      | 25Mb 4-wire serial interface,<br>up to 55mA current per output,<br>fault detection, high dissipation<br>package, -40°C to +125°C<br>operation        | Eases design of robust control panel indicators.   |
| UARTs                  |   |  |  |
| MAX3108                | Serial UART, SPI, I <sup>2</sup> C compatible                 | 24Mbps (max) data rate, 128-<br>word FIFOs, automatic RS-485<br>transceiver control, 4 GPIOs, 24-pin<br>SSOP or small 3.5mm x 3.5mm<br>TQFN packages | Reduces host controller<br>performance requirements and<br>cost.                                   |

# **Calibration and Automated Calibration**

The goal of calibration is to maintain a piece of equipment in its most accurate state. The goal of automated calibration is to improve efficiency and consistency of the calibration process, while minimizing the down time required to verify equipment performance.

## **Accuracy vs. Precision**

The terms accuracy and precision are often used synonymously, but they are not the same thing. Both are, however, needed to achieve the best results. We can illustrate the differences between these two terms through the following example. To measure the performance of a particular system, one can plot the results of a large number of samples over time on a graph and note the differences between the actual results and the desired result (Figure 1). Accuracy is the measure of how close the mean of the total set of results is to the desired result. Precision is a measure of the spread of these results relative to this mean. Precision only addresses how dispersed the results are, not how far they are from the average of the desired value.



Calibration usually addresses accuracy and less often precision. From the above discussion it is evident that calibration may not have any effect on precision, because other circuit parameters such as noise may have an influence on precision and no amount of calibration will reduce the spread of values. This is of course not always the case, such as in light beam focusing. When a beam is correctly focused, its spread is reduced. This is, of course, not always the case.

For complete basic calibration, it is often required to correct for both offset and span (gain). This requires calibration at more than one point. If a system is linear, calibration at two points will suffice since two points define a line (**Figure 2**). If a system is nonlinear, more calibration points are needed.

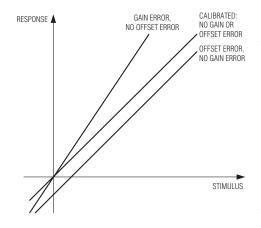


Figure 2. For proper basic calibration, the system response to stimuli must be corrected for both offset and gain errors. Offset errors do not produce a zero output for a zero input. Gain errors (when no offset error remains) show more deviation from the expected results at larger input stimuli.

Calibration is the process of adjusting circuit parameters, such as offsets and gains, to make equipment meet specifications or a standard. All organizations producing electronic goods must either design with high-precision components or use some form of calibration.

All electronic products must pass at least minimal signal testing prior to shipping to ensure that the product works out of the box. A rigorous test and calibration process also reduces liability from performance errors and provides a paper trail that shows that industry and regulatory requirements have been followed.

Although new products may meet strenuous requirements for calibration, due to the effects of use, wear, and environmental conditions, over time products may no longer meet specifications. For some products the effect is easily seen: a cell phone that no longer receives calls, or a hard drive that loses data. For others, e.g., a voltmeter with a small drift, the effect cannot be easily seen, but the impact may be costly. Or, in the case of an insulin pump, the impact may be even dangerous. For many types of industrial (and medical) electronic equipment, calibration is an on-going process and is the reason why many products are now being designed with self-calibration circuitry.

For control devices used in a production environment, a proper calibration process uses test equipment that has been certified to standards traceable to a government agency. In the U.S. this agency is the National Institute of Standards and Technology (NIST). This type of certified calibration requires the services of a certified metrology lab. The lab will not only calibrate the equipment based upon recognized standards, but will also provide reports as part of their service. These reports prove that the equipment has been measured and adjusted relative to a chain of standards traceable back to the government's master standards.

Figure 1. Accuracy and precision are two very different things.

PRECISION

MEASURED

VALUES

NUMBER OF

**OCCURRENCES** 

ACCURACY

# Test Equipment Calibration

While calibration of the end product is required to establish its performance, the production test equipment used to calibrate it must, of course, also be operating within its specifications (Figure 3). This calibration is maintained with more accurate test equipment and reference standards used only occasionally for this purpose. Eventually these standards must also be calibrated. As one moves further back in the chain, the equipment gets more accurate and more sensitive, usually by an order of magnitude or at least 4:1 at each stage, so it must be treated with more care to avoid "knocking" it out of calibration.

Today test equipment is being built with new techniques that reduce or eliminate calibration expenses or downtime. These techniques, called electronic or automated calibration, use self-calibration or digital calibration.

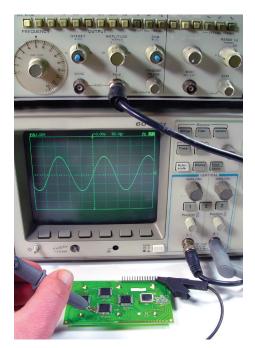


Figure 3. An oscilloscope has many functions to be calibrated in the instrument and on the probe itself. Voltage probes usually have a compensation adjustment for proper frequency response. A true square wave is generated by the scope to test this probe setting. Internal self-tests and self-calibrations are common, but use of known good external standards is still periodically needed for calibration certification.

## Benefits of Automated Calibration

Automated calibration can reduce cost in many areas. It does this by removing manufacturing tolerances, allowing the use of less expensive components, reducing test time, improving reliability, increasing customer satisfaction, reducing customer returns, lowering warranty costs, and increasing the speed of product delivery.

#### Automated Calibration Characteristics

Automated calibration is built around circuitry that is designed into the end equipment for the explicit purpose of maintaining calibration. This circuitry can take a variety of forms and functions. For example, this circuitry could utilize digital communication between the end equipment and a remote host or a factory test system. Once communication is established, the end equipment uploads data to the host and then through commands and downloaded data, the host calibrates the end equipment's circuit parameters. Or, the circuitry could be completely internal to the equipment itself. In this latter case, the circuitry might measure an imbedded precision component, such as a precision resistor or voltage reference, to allow adjustment and verification of the accuracy of the signal chain components.

Testing and calibration generally fall into three broad areas:

- 1. Production-line final-test calibration
- 2. Periodic self-testing
- Continuous monitoring and readjustment

Automated and electronic calibration can be cost effective in each area.

#### **Final-Test Calibration**

When a circuit is developed in the lab, typically 20 to 50 devices are prototyped and tested. All signal levels are measured, and variances and tolerance margins are noted. However, when the product goes into production, hundreds of thousands or even millions of devices are built and they do not receive the same level of testing for proper signal levels, variances, and tolerance margins.

All practical components, both mechanical and electronic, have manufacturing tolerances. The more relaxed the tolerance, the more affordable the component. When components are assembled into a system, the individual tolerances accumulate to create a total system error tolerance. When thousands of devices are manufactured, the errors can multiply so that a properly manufactured product may not work. If this happens enough to reduce yields, then profitability is affected. Through the proper design of trim, adjustment, and calibration circuits, it is possible to correct for the worst-case tolerance stackups, thereby ensuring that a higher percentage of products can be made to meet specifications upon exiting the assembly line.

Final-test calibration corrects for these errors. Multiple adjustments may be required to calibrate the device under test (DUT) to meet specifications.

For example, suppose the design engineers find that they can use  $\pm 5\%$ resistors and a low-cost op amp because their Monte Carlo testing shows that even under worst-case tolerance stackup, the use of two low-cost digital potentiometers (pots) for offset and gain can calibrate out all the variation from the components chosen. They also see that to eliminate the adjustability altogether, they would have to use expensive tight tolerance resistors and a precision op amp. With this knowledge, they decide to use the circuits as-is and to simply adjust the offset and span (gain) during final test to meet system specifications. By using digital pots instead of mechanical pots, they avoid using human labor to make the adjustments.

#### **Periodic Self-Testing**

Environmental influences in the field can create a need for test and calibration.

Such environmental factors include temperature, humidity, vibration, contamination, and component aging. These factors are accounted for with a combination of self-test at power-up and periodic or continuous testing. The field testing can be as simple as sensing temperature and compensating accordingly, or it can be more complex.

A simple example of power-up selftesting is to automatically briefly short the inputs of an amplifier together to set a zero reading point (Figure 4). Doing so allows any changes to input offset voltage or to downstream circuit parameters to be calibrated out. Another example is to electronically swap the resistive temperature sensor with a precision fixed resistor to enable the instrument to calibrate the temperature reading to the expected value. Using two different precision resistors can establish a line that provides both gain and offset information. More complex schemes can be used to adjust for nonlinearities.

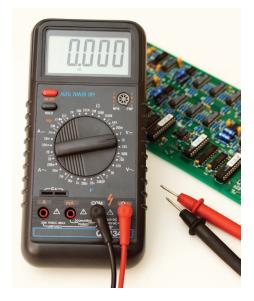


Figure 4. A digital multimeter showing good calibration of the zero signal level, but is the gain calibrated? This is difficult to discern without a reference standard to read periodically. Or, maybe during power-up it reads a precision internal value while the display is blanked to check for proper gain calibration?

#### Continuous Monitoring and Readjustment

In some applications, waiting for periodic calibration at power-up would

occur only very rarely after system maintenance which can be too costly if system performance is suffering or safety margins are compromised from an out of calibration component. Depending on the impact of a system not being calibrated, these applications may need to use continuous monitoring with subsequent readjustment. Good examples of applications that requires continuous monitoring and calibration are a variety of safety systems in nuclear power plants.

Continuous calibration consists of circuitry that self-corrects continuously or very frequently. This can be accomplished in a variety of ways either with techniques similar to periodic self-testing, just done more frequently, or with other techniques that allow the system to continue to operate. In the former case, very brief interruptions to the normal signal path may be made, including making connections to simulate zero scale and full scale readings for example. Another use of these interruptions would be, for example, to cut a signal path gain in half and check that the response is indeed exactly half. If not, an offset error is indicated and can be corrected for. In the latter case, where full system operation needs to be maintained, out-of-band or noise level techniques can be used by injecting signals either above or below the normal signal frequency range, or signals so small that they fall within the noise floor of the system. With proper design, these signals are detectable by a variety of methods. These can be used to stimulate the test and calibration protocol while standard signal processing continues. The techniques used are limited only by the creativity of the engineers. If a system, during a readjustment, detects that no further adjustment is possible, then an alarm condition must be set.

The ability to adjust analog outputs using digital technology has greatly enhanced the ability to continuously monitor and adjust. Digital technology provides low-cost and nearly errorfree communications for remote monitoring and subsequent control. Digital control of analog circuitry using precision DACs and digital pots allows economical remote-control processes, while also ensuring the precision needed to meet specifications.

### Circuitry for Electronic and Automated Calibration

Electronic calibration is based on digitally controlled calibration devices: DACs with voltage or current outputs can be used to provide temporary inputs to analog signal chains or to adjust bias levels. Digital pots with variable resistances or variable resistance ratios can provide gain and offset adjustments, analog switches can select different gain or filter corner setting components, and potentially any other digital-toanalog transducer such as a digitally controlled light source can be used to stimulate a self-calibration process. All of these replace mechanical calibration procedures in factory settings and within the equipment itself. The digital approach provides a range of benefits: better reliability, improved employee safety, increased dependability, and reduced product liability expense. In addition, digitally controlled calibration can be fully automated, which results in reduced test time and expense by removing human error.

Solid state solutions such as digital pots as opposed to mechanical pots are not susceptible to mechanical shock and vibration, which can cause loss of calibration settings and, in the case of mechanical pots, can cause momentary wiper contact bounce which will likely lead to unpredictable and potentially dangerous behavior.

Analog switches have improved to the point that their on-resistance is low enough that they can be used in high-precision gain setting circuits to provide a range of precision fixed-gain choices. This capability, combined with a digital pot for fine adjustments within a gain range, can provide an extremely precise calibration capability.

# Implementing Electronic Calibration

Digital pots, which can guarantee 50,000 write cycles, allow periodic adjustments to occur repeatedly over long equipment life spans. Conversely, the best mechanical pots can support only a few thousand adjustments. Location flexibility and size are also advantages. Digitally adjustable pots can be mounted on the circuit board directly in the signal path, exactly where they are needed. In contrast, mechanical pots require human access, which can necessitate placing them in nonoptimal locations that result in long circuit traces or with designers having to resort to using coaxial cables to make the proper noise-shielded connections. In sensitive circuits, the capacitance, time delay, or interference pickup of these connections can reduce equipment precision.

Digital pots used in electronic calibration schemes can be fundamental in eliminating these types of problems. In addition, calibration DACs (CDACs) and calibration digital pots (CDPots) also enable electronic trimming, adjustment, and calibration. These calibration-specific devices often employ internal nonvolatile memory, which automatically restores the calibration setting during power-up and provides the ability to customize the calibration granularity to match the application.

For extra safety, one-time programmable (OTP) CDPots are available. These devices can permanently lock in the calibration setting, preventing an operator from making further adjustments. To change the calibration value, the device must be physically replaced. A special variant of the OTP CDPot always returns to its stored value upon power-on reset, while allowing operators to make limited adjustments during operation at their discretion.

# Leveraging Precision Voltage References for Digital Calibration

Sensor and voltage measurements with precision ADCs are only as good as the voltage reference used for comparison. Likewise, output control signals are only as accurate as the reference voltage supplied to the DAC, amplifier, or cable driver.

Common power supplies are not adequate to act as precision voltage references. They typically are not designed to meet the accuracy, temperature coefficients, and noise specifications needed in a voltage reference. All voltage sources have some imperfect specifications for power-supply rejection ratio (PSRR) and for load regulation, but typically a voltage reference will have very good PSRR specifications. The load range allowed is usually far less than a power supply's load range, which reduces its output voltage tolerance. No control system can have infinite gain while remaining stable, so there will always be some loading effect on the output voltage of a voltage reference.

Compact, low-power, low-noise, and low-temperature-coefficient voltage references are affordable and easy to use. In addition, some references have internal temperature sensors to aid in the compensation for this environmental variable. Voltage references with "force" and "sense" pins further improve accuracy by removing the slight voltage effects of ground currents in the circuit.

In general, there are three kinds of serial calibration voltage references (CRefs), each of which offers unique advantages for different factory applications. Having a choice of serial voltage references enables the designer to optimize and calibrate with high accuracy. The first type of reference, a trimmable CRef, enables a small trim range, typically 3% to 6%. This is an advantage for gain trim in industrial imaging systems. For instance, coupling a video DAC with a trimmable CRef allows the overall system gain to be fine-tuned by simply adjusting the CRef voltage.

The second type, an adjustable reference, allows adjustment over a wide range (e.g., 1V to 12V), which is advantageous for field devices that have wide-tolerance sensors and that must operate on unstable power. Some examples, such as portable maintenance devices, may need to operate from batteries, automotive power, or emergency power generators.

The third type, called an  $E^2$ Ref, integrates memory, allowing a singlepin command to copy any voltage between 0.3V and (V<sub>IN</sub> - 0.3V) and, then, to infinitely hold that level.  $E^2$ Refs benefit test and monitoring instruments that need to establish a baseline or warning-alert threshold.

### **Summary**

Electronic and automated calibration techniques are becoming mainstream because they make production more efficient and products last longer. New products like CDACs and lower cost precision DACs, digital pots, and CRefs from Maxim provide an economical way to incorporate calibration circuitry directly into end products to minimize downtime, reduce costs, and improve long-term performance, even under harsh operating conditions.

# **Recommended Solutions**

| Part                          | Description  | Features  | Benefits   |
|-------------------------------|--|---|--|
| CDPots                        |  |   |  |
| MAX5481                       | 1024-tap (10-bit) CDPot with SPI or up/down interface                  | 1.0μA (max) in standby, 400μA<br>(max) during memory write  | Minimal power use for battery-<br>operated portable devices.   |
| MAX5477                       | Dual, 256-step (8-bit) CDPot with I <sup>2</sup> C interface           | EEPROM write protection, single-<br>supply operation (2.7V to 5.25V)  | EEPROM protection retains calibration data for safety.   |
| MAX5422                       | Single, 256-step (8-bit) CDPot with SPI interface                      | Tiny (3mm x 3mm) TDFN package   | Saves PCB space for portable products.   |
| MAX5427                       | 32-step (5-bit), OTP CDPot   | OTP or OTP plus adjustment  | Versatile, reduces component count by performing two functions.  |
| DS3502                        | 128-step (7-bit) CDPot with I <sup>2</sup> C interface                 | High output voltage range (up to 15.5V)   | Permits direct calibration of high-voltage circuits.   |
| CDACs                         |  |   |  |
| MAX5105, MAX5115              | Quad, 8-bit CDACs with<br>independent high and low<br>reference inputs | Rail-to-rail output buffers, choice of I <sup>2</sup> C or SPI interface                                      | Selectable voltage range improves granularity and prevents unsafe adjustments.   |
| MAX5106                       | Quad, 8-bit CDAC with<br>independently adjustable voltage<br>ranges    | Allows customization of calibration granularity, small 5mm x 6mm package                                      | Saves PCB space for portable products.   |
| MAX5214/MAX5216               | Ultra-low-power, 1-channel,<br>14-/16-bit voltage-output DACs          | Quiescent current < 80µA max, SPI<br>interface  | High resolution and external<br>reference provides fine granularity<br>and flexibility for automated<br>calibration systems. |
| MAX5715*                      | Quad, 8-/10-/12-bit DACs with internal reference                       | 8-/10-/12-bit voltage-output DAC,<br>three-voltage-selectable internal<br>reference, SPI interface            | High integration provides multiple calibration points in a small space.  |
| MAX5725*                      | Octal, 12-bit DAC with watchdog timer and internal reference           | 8-/10-/12-bit resolution, selectable internal reference, watchdog timer, SPI interface                        | Watchdog timer allows resets to defined calibration levels in event of communication failure.                                |
| CRefs and E <sup>2</sup> Refs |  |   |  |
| MAX6160                       | Adjustable CRef (1.23V to 12.4V)                                       | Low 200mV dropout, 75µA supply current is virtually independent of input-voltage variations                   | Longer battery life in portable equipment.   |
| MAX6037                       | Adjustable CRef (1.184V to 5V)   | Shutdown mode (500nA, max), low<br>100mV (max) dropout at 1mA load,<br>5-pin SOT23 (9mm <sup>2</sup> )        | Battery friendly and small size for portable applications.   |
| MAX6173                       | Precise voltage reference with temperature sensor                      | ±0.05% (max) initial accuracy,<br>±3ppm/°C (max) temperature<br>stability                                     | Allows analog system gain trim<br>while maintaining the digital<br>accuracy of ADCs and DACs.                                |
| MAX6220                       | Low-noise, precision voltage reference                                 | 8V to 40V input-voltage range, ultra-low 1.5 $\mu V_{P-P}$ noise (0.1Hz to 10Hz)                              | Dependable operation from<br>unstable power (batteries,<br>automotive power, or emergency<br>power generators).              |
| DS4303                        | Electronically programmable voltage reference                          | Wide, adjustable output voltage<br>range can be set within 300mV<br>of the supply rails with ±1mV<br>accuracy | A calibration voltage is memorized forever using one simple GPIO pin.  |

# Legal Notices

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