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Overview of Industrial Motor Control Systems

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Abstract: This overview of industrial motor controls highlights the differences and subsystems for DC motor, brushless DC, and AC induction motors. An in-depth analysis of critical subsystems focuses on monitoring and measuring current; sensing temperature; sensing motor speed, position, and movement; monitoring and controlling multichannel currents and voltages; and high-accuracy motor control with encoder data interfaces.

Electric motors consume almost 50% of the world's electricity. With the cost of energy rising steadily, industry is focused on replacing inefficient constant-speed motors and drives with microprocessor-based, variable-speed drives. This new motor-control technology will reduce energy consumption by more than 30% compared to the older drives. While these variable-speed controllers add cost to a motor, the forecasted energy savings and increased motor functionality should easily offset those initial expenses within a few years.

Popular Motor Designs

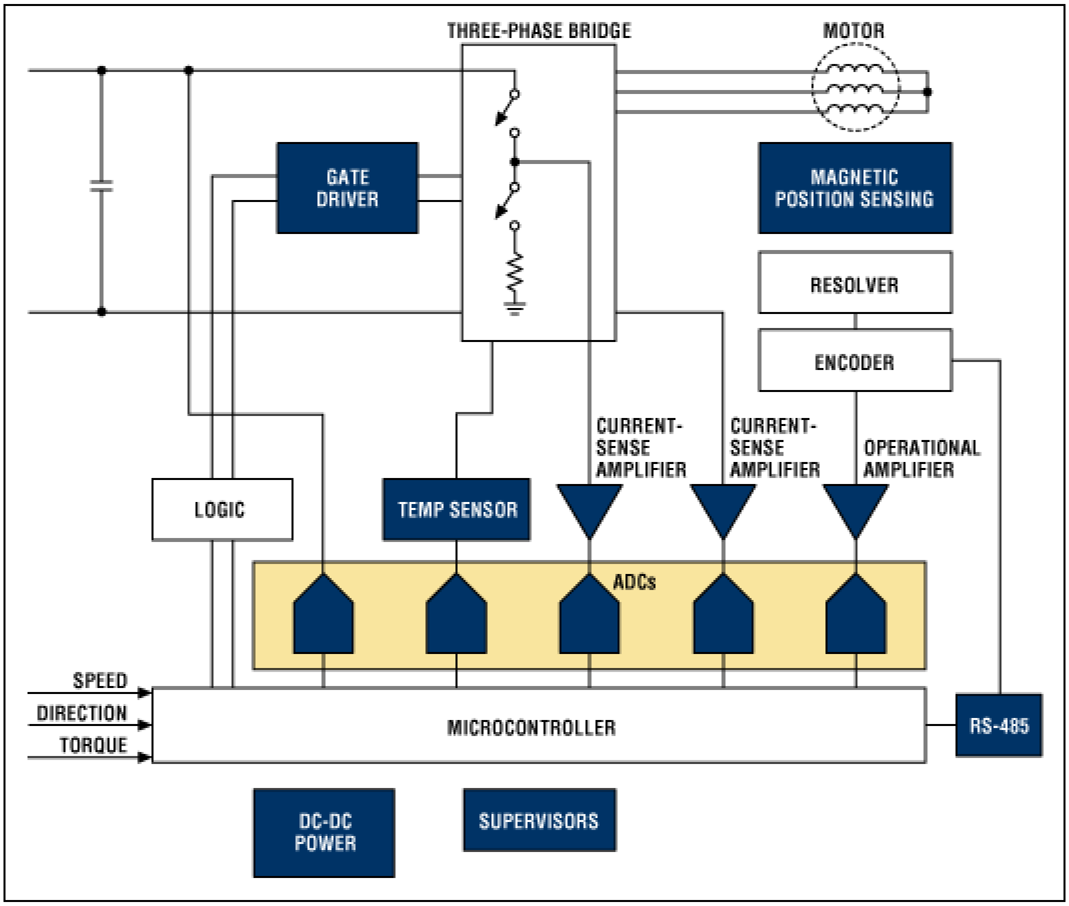
The DC motor, brushless DC, and AC induction motor are the popular motor designs used in today's industrial applications. Each of these motor types has its own unique characteristics, but they all operate on the same basic electromagnetic principle: when a conductor carrying current, such as a wire winding, is located in an external magnetic field perpendicular to the conductor, then the conductor will experience a force perpendicular to itself and to the external magnetic field.

DC Motors: Low Cost and Accurate Drive Performance

A DC motor was among the first motor types put to practical use, and it is still popular where low initial cost and excellent drive performance are required. In its simplest form, the stator (i.e., the stationary part of the motor) is a permanent magnet, and the rotor (i.e., the rotating part of the motor) carries an armature winding connected to a mechanical commutator which switches current on and off to the winding. The magnet establishes the field flux which interacts with the armature current to produce the electromagnetic torque, thereby enabling the motor to perform work. The motor's speed is controlled by adjusting the DC voltage applied to the armature winding.

Depending on the application, a full-bridge, half-bridge, or just a step-down converter is used to drive the armature winding. The switches in these converters are pulse-width modulated (PWMed) to achieve the desired voltage. Maxim's high-side or bridge-driver ICs like the MAX15024/MAX15025 can be used to drive the FETs in the full- or half-bridge circuit.

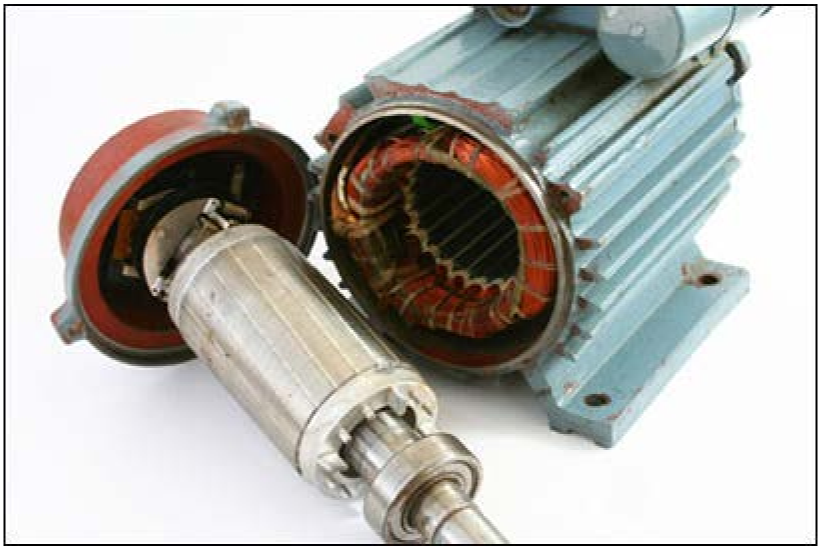
DC motors are also widely used in servo applications where speed and accuracy are important. To meet speed and accuracy requirements, microprocessor-based closed-loop control and information about rotor position are essential. Maxim's MAX9641 Hall-effect sensor provides information about rotor position.



Block diagram of a typical industrial motor control. For a list of Maxim's recommended motor-drive solutions, please go to: www.maximintegrated.com/motordrive.

AC Induction Motors: Simplicity and Ruggedness

An AC induction motor is popular in industry because of its simplicity and ruggedness. In its simplest form, this motor is a transformer with the primary-side voltage connected to the AC-power-voltage source and the secondary side shorted to carry the induced secondary current. The name "induction" motor derives from this induced secondary current. The stator carries a three-phase winding and the rotor is a simple design, commonly called a "squirrel cage" in which the copper or aluminum bars are short circuited at both the ends by cast-aluminum end rings. The absence of rotor windings and brushes makes this motor design especially reliable.


Rotor and stator of an induction motor.

When operated from the 60Hz voltage, the induction motor operates at a constant speed. However, when power electronics and a microprocessor-based system are used, the motor's speed can be varied. The variable-speed drive consists of an inverter, signal conditioner, and microprocessor-based control. The inverter uses three half bridges in which the top and the bottom switch are controlled in a complementary fashion. Maxim offers multiple half-bridge drivers like the MAX15024/MAX15025 which control the top and bottom FETs independently.

Precise measurement of three-phase motor current, rotor position, and rotor speed are necessary for efficient closed-loop control of an induction motor. Maxim offers many high-side and low-side current amplifiers, Hall-effect sensors, and simultaneous-sampling analog-to-digital converters (ADCs) to accurately measure these parameters in the harshest environments.

A microprocessor uses data on the current and position to generate logic signals for the three-phase bridge. A popular closed-loop control technique called vector control decouples the vectors of field current from the stator flux so that it can be controlled independently to provide a fast transient response.

Brushless DC Motors: High Reliability and High-Output Power

A brushless DC (BLDC) motor has neither commutator nor brushes, so it requires less maintenance than a DC motor. It also offers more output power per frame size compared to induction and DC motors.

The stator of the BLDC motor is quite similar to that of the induction motor. The BLDC motor's rotor, however, can take different forms but all are permanent magnets. Air-gap flux is fixed by the magnet and is unaffected by the stator current. The BLDC motor also requires some form of rotor position sensing. A Hall-effect device embedded in the stator is commonly used to sense the rotor's position. When the rotor's magnetic pole passes near the Hall-effect sensors, a signal indicates whether the north or the south pole passed. Maxim offers several Halleffect sensors like the MAX9641, which simplifies designs and reduces system costs by integrating two Hall-effect sensors and digital logic to provide both positional and directional outputs of the magnet.

The Importance of Sensors, Signal Conversion, and Data Interfaces

Several types of sensors provide feedback information in the motor-control loop. These sensors also improve reliability by detecting fault conditions that can damage the motor. The following sections examine the role of sensors in motor control in greater detail. Specific attention will be given to current-sense amplifiers, Hall-effect sensors, and variable-reluctance (VR) sensors. Other important topics include monitoring and controlling multichannel currents and voltages with high-speed analog-to-digital signal conversion (ADCs), and the encoder data interfaces needed for high-accuracy motor control.

Monitoring and Measuring Current for Optimal Motor Control

Current Monitoring

Current is a common signal to be sensed, monitored, and fed back to the motor-control loop. Current-sense amplifiers make it easier to monitor the current into and out of the system with a high level of precision. If current-sense amplifiers are used, no transducer is needed, as the electrical signal itself is being measured. Current-sense amplifiers detect shorts and transients, and they monitor power and reverse-battery conditions.

Current Measurement

There is a variety of techniques to measure current, but by far the most popular uses a current-sense resistor. In this technique the voltage drop across the current-sense resistor is first amplified by an op amp set up in a differential gain stage, and then measured. Traditionally, this approach has been implemented with discrete components. However, discrete solutions also introduce some disadvantages such as the requirement for matched resistors, poor drift, and a larger solution area. Fortunately, these multiple and varied disadvantages can be overcome by integrating current-sense amplifiers into the design. Not only do the amplifiers measure the current, but they also sense the direction of current, accommodate wide common-mode ranges, and provide more precise measurement.

Current measurement employs either the low-side principle in which the sense resistor connects in series with the ground path, or the high-side principle in which the sense resistor connects in series with the hot wire. In low-side measurement, the circuit has a low-input common-mode voltage and the output voltage is ground referenced. The low-side resistor adds undesirable extraneous resistance in the ground path. In high-side measurement, the load is grounded but the high-side resistor must cope with relatively large common-mode signals. High-side sensing also allows detection of fault conditions such as the motor case or winding that shorts to ground.

High-side current-sense amplifiers like the MAX4080/MAX4081 employ a current-sensing resistor placed between the positive terminal of the power supply and the supply input of the monitored circuit. This arrangement avoids extraneous resistance in the ground plane, greatly simplifies the layout, and generally improves the overall circuit performance. Maxim's unidirectional and bidirectional current-sense ICs like the MAX9918/MAX9919/MAX9920 are available with or without internal sense resistors. This variety of parts adds considerable flexibility to designs and simplifies part selection for a wide variety of ADCs and applications.

Sensing Motor Speed, Position, and Movement

Hall-effect sensors are used to sense the speed, position, and direction of motors. With integrated device logic, the sensors then communicate that data to the system for real-time feedback. The sensor also detects and reports any interruption to the motor so corrective action can be taken. Typically, to detect the direction of movement two Hall-effect sensors are used.

Commutation can be synchronized to Hall edges if the system has the same number of Hall-effect devices as motor phases and if the mechanical geometry of the Hall-effect devices is correlated with the electrical geometry of the motor phases. Maxim's MAX9641 combines two Hall-effect sensors and sensor signal conditioning to provide both positional and directional outputs.

Hall-effect sensors can also be used with special Hall-effect sensor interface products like the MAX9621. The interface devices provide several functions: protect against supply transients, sense and filter the current drawn by the Hall-effect sensors, and diagnose and protect against faults.

Hall-effect sensors improve robustness and repeatability, compared to mechanical photointerrupter-based systems which are compromised in environments with dust and humidity. Since Hall-effect sensors detect the magnetic field produced by a magnet or current, they can operate continuously in such harsh environmental conditions.

In some applications vibration, dust, and high temperature cause active sensors to operate improperly. In these situations passive elements can be used to sense the motor's operation and feed that data to the system with an interface IC. Alternatively, variable-reluctance (VR) sensors can be used in these extreme operating conditions.

VR sensors like the MAX9924—MAX9927 have a coil to sense the speed and rotation of motors. When the toothed wheel of the shaft attached to a motor passes by the face of the magnet, the amount of magnetic flux passing through the magnet and, consequently, the coil varies. When the tooth is close to the sensor, the flux is at a maximum. When the tooth is further away, the flux drops off. The rotating toothed wheel results in a time-varying flux that induces a proportional voltage in the coil. Subsequent electronics then process this signal to get a digital waveform that can be counted and timed more readily. Integrated VR-sensor interface solutions possess many advantages over other solutions, including enhanced noise immunity and accurate phase information.

Monitoring and Controlling Multichannel Currents and Voltages

To monitor and control a motor, multiple currents and voltages need to be measured and the phase integrity between the channels preserved. Designers are faced with two choices for the ADC architecture: use multiple single-channel ADCs in parallel, a design that makes it very difficult to synch up the conversion timing; or use a simultaneous-sampling ADC. The simultaneous-sampling architecture uses either multiple ADCs in a single package, all with a single conversion trigger or with multiple sample-and-hold amplifiers (also referred to as track-and-hold amplifiers) on the analog inputs. In the case of multiple sample-and-hold amplifiers, a multiplexer is still used between the multiple analog inputs and the single ADC. Simultaneous sampling eliminates the need for complicated digital-signal-processing algorithms.

Sampling speeds of 100ksps or more are common for motor-control applications. At these speeds the

ADC continuously monitors the motor for any indication of errors or potential damage. At the first sign of trouble, the system can correct itself or shut down when necessary. If the ADC does not sample fast enough, an error condition might not be identified early enough to be addressed.

The amount of dynamic measurement range varies for each motor-control application. In some cases 12 bits of resolution are sufficient. For the more precise motor-control applications, however, 16 bits of resolution are a more common standard. A high-performance 16-bit ADC like the MAX11044 or MAX11049 allows a system to achieve better than 90dB of dynamic range.

Maxim offers a broad portfolio of simultaneous-sampling ADCs designed for motor control. Devices have both serial and parallel interfaces, and 12-, 14-, or 16-bit operation.

High-Accuracy Motor Control with Encoder Data Interfaces

The accuracy with which a motor needs to be controlled depends on the system requirements. In some applications the accuracy requirements are very high, as in industrial robotics or in bottling. A welding robot, for example, is expected to operate with high speed and high precision. Similarly, the motors in a bottling factory must be controlled accurately so that bottles are stopped at the right position for filling, capping, and labeling. To control a motor precisely, the rotor's speed, direction, and position have to be determined. These can be monitored with analog sensors like resolvers, synchros, RVDTs, or rotary potentiometers. High accuracy is obtained with the use of encoders like optical encoders and Hall-effect sensors. Encoders provide the controller with incremental and/or absolute shaft-angle information.

A motor controller, commonly implemented algorithmically by a digital signal processor (DSP), calculates the rotor's present speed and angle. It adjusts the actuating power stages to achieve the desired response efficiently and optimally. This feedback control loop requires robust and reliable information from the sensor, typically communicated over long cables from the encoder to the controller.

Incremental information is typically transmitted to the controller by quadrature signals, i.e., two signals phase shifted by 90°. These signals can be in analog form (sine + cosine) or in binary form. Absolute position information, in contrast, is only communicated by a serialized binary data stream through RS-482 or RS-422.

As the working environments are harsh, the data paths need to be robust and reliable. EMI levels are high, which explains the use of differential signaling. High temperatures are commonly encountered due to the proximity to the motor.

Maxim's extensive range of RS-485/RS-422 and PROFIBUS interface devices are targeted for these motor-control applications. Interface devices like the MAX14840E high-speed RS-485 transceiver exhibit the high-signal integrity and robustness expected for stringent safety control and for sustaining the up-time of large capital investments.

Related Parts		
MAX11044	4-/6-/8-Channel, 16-/14-Bit, Simultaneous-Sampling ADCs	Free Samples
MAX11045	4-/6-/8-Channel, 16-/14-Bit, Simultaneous-Sampling ADCs	Free Samples
MAX11046	4-/6-/8-Channel, 16-/14-Bit, Simultaneous-Sampling ADCs	Free Samples
MAX11047	4-/6-/8-Channel, 16-/14-Bit, Simultaneous-Sampling ADCs	Free Samples
MAX11048	4-/6-/8-Channel, 16-/14-Bit, Simultaneous-Sampling ADCs	Free Samples
MAX11049	4-/6-/8-Channel, 16-/14-Bit, Simultaneous-Sampling ADCs	Free Samples
MAX13442E	±80V Fault Protected RS-485 Half-Duplex Transceiver with Foldback Current Limit	Free Samples
MAX13443E	±80V Fault Protected RS-485 Half-Duplex Transceiver with Foldback Current Limit	Free Samples
MAX13448E	±80V Fault-Protected, Full-Duplex RS-485 Transceiver	Free Samples

MAX1377	Dual, 12-Bit, 1.25Msps, Simultaneous-Sampling ADCs with Serial Interface	Free Samples
MAX1379	Dual, 12-Bit, 1.25Msps, Simultaneous-Sampling ADCs with Serial Interface	Free Samples
MAX1383	Dual, 12-Bit, 1.25Msps, Simultaneous-Sampling ADCs with Serial Interface	Free Samples
MAX14770E	High-ESD PROFIBUS RS-485 Transceiver	Free Samples
MAX14840E	40Mbps, +3.3V, RS-485 Half-Duplex Transceivers	Free Samples
MAX14841E	40Mbps, +3.3V, RS-485 Half-Duplex Transceivers	Free Samples
MAX3430	±80V Fault-Protected, Fail-Safe, 1/4-Unit Load, +3.3V RS-485 Transceiver	Free Samples
MAX3440E	±15kV ESD-Protected, ±60V Fault-Protected, 10Mbps, Fail-Safe RS-485/J1708 Transceivers	Free Samples
MAX3444E	±15kV ESD-Protected, ±60V Fault-Protected, 10Mbps, Fail-Safe RS-485/J1708 Transceivers	Free Samples
MAX9621	Dual, 2-Wire Hall-Effect Sensor Interface with Analog and Digital Outputs	Free Samples
MAX9641	Low-Power, Dual Hall-Effect Sensor	
MAX9918	-20V to +75V Input Range, Precision Uni-/Bidirectional, Current-Sense Amplifiers	Free Samples
MAX9919	-20V to +75V Input Range, Precision Uni-/Bidirectional, Current-Sense Amplifiers	Free Samples
MAX9920	-20V to +75V Input Range, Precision Uni-/Bidirectional, Current-Sense Amplifiers	Free Samples
MAX9924	Variable-Reluctance Sensor Interface with Differential Input and Adaptive Peak Threshold	Free Samples
MAX9925	Variable-Reluctance Sensor Interface with Differential Input and Adaptive Peak Threshold	Free Samples
MAX9926	Variable-Reluctance Sensor Interface with Differential Input and Adaptive Peak Threshold	Free Samples
MAX9927	Variable-Reluctance Sensor Interface with Differential Input and Adaptive Peak Threshold	Free Samples

More Information
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For Samples: http://www.maximintegrated.com/samples
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