Ecosystem for Optimizing Energy Efficiency in Factory Production Systems

by Aengus Murray

International energy reports show that in 2006 electric motors consumed more than 46% of the world's electricity corresponding to 6040 Mt of CO_2 emissions[1]. This has led to demands on motor drive manufacturers to add advanced control functions and tools to support system energy efficiency optimization. A new motor drive ecosystem for optimizing energy efficiency in factory production systems is gaining widespread acceptance worldwide. The good news for Europe is that, thanks to energy conservation policies, industrial electricity consumption is now on a downward trend at a rate of 1% per year[2].

The most common uses of motors in factories are in pumps, fans, compressors, and conveyers with a majority of these motors available as standard catalog products. Small motors (under 0.75 kW) used in small machines and appliances are 90% of the total global stock, but account for less than 10% of motor energy consumption. However, medium size (0.75 kW to 350 kW) industrial motors account for almost 70% of the world's motor energy consumption. In a typical application, only 50% of the electrical energy consumed by the system is converted to useful mechanical energy, and this has attracted the attention of both energy regulators and factory operators across the world. Regulatory agencies in the United States, China, Europe, and elsewhere have introduced minimum energy performance standards (MEPS) over the past number of years. Premium motor rated efficiency levels now range from 80% at the lowest power range to 96% in the largest motors, so factory operators are looking beyond the motor to secure energy savings.

Figure 1 describes the main elements in an automated machine or process found in a modern factory. This approach provides a new capability to optimize the operation of machines and processes to add new levels of efficiency in energy and productivity.

There are multiple control layers that determine the efficiency of the motors and the overall production process. The first control layer adjusts the power inverter switching sequence to control the motor voltage and current, as well as maximize torque production efficiency. Next is the position and speed controller that operates the machine efficiently. In process equipment, this could be driving the optimum pump flow rate, while in automation equipment this could be a sequence of speed or position commands to execute an assembly function. In the latter case, the response time of the speed control can be more critical to the machine controller than the efficiency of torque production. The communications and systems layer is growing in importance as multiple motors are now synchronized over high speed data networks, also connected to the factory network. Process managers can start machines in sequence as they are needed, rather than having them waiting in idle mode. Networked safety functions enable efficient starting and stopping of
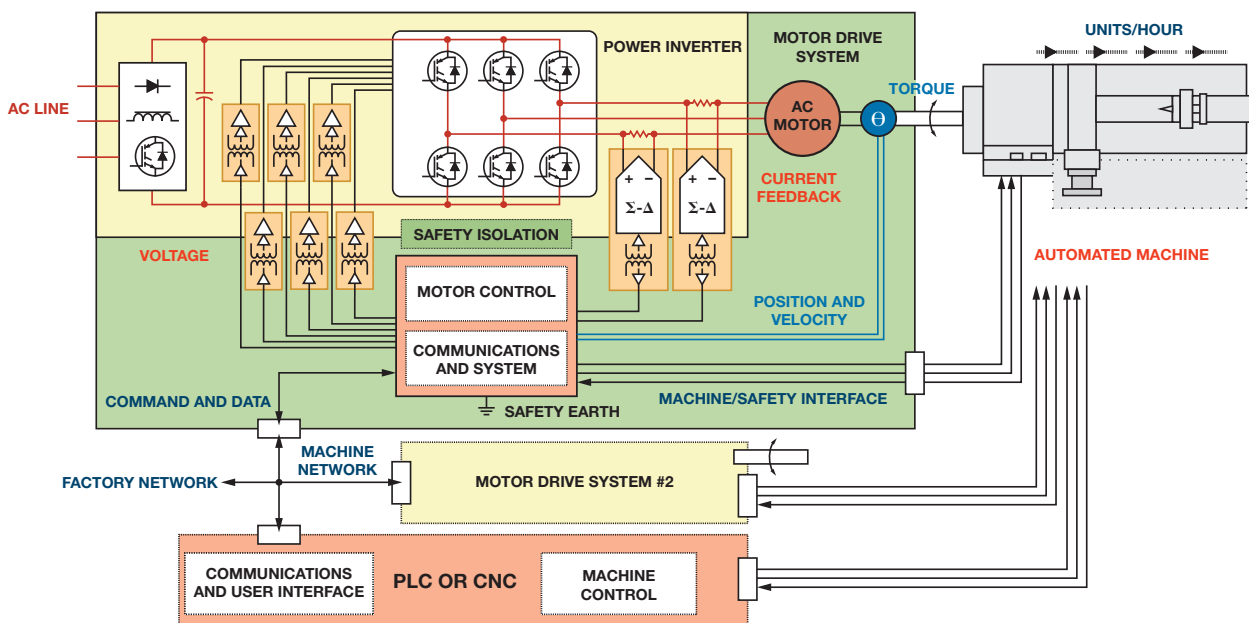

Figure 1. Automated machine control requires multiple feedback control loops and a safety isolation barrier between the power inverter, control, and communication circuits.

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equipment, minimizing downtime. Plant managers track motor drive operational and diagnostic data to improve process energy efficiency and reliability.

Efficient Torque Production: Algorithms and Ethernet

Motor efficiency is a function of the torque produced per amp, supplied at any given speed and terminal voltage. Electric motors produce torque through forces that tend to pull their internal magnetic fields into alignment. In the ac motors in Figure 2, these forces are generated through the interaction of stator and rotor magnetic fields. The ac motors produce a constant torque when the stator currents are synchronized with the rotor motion to maintain continuous field misalignment. The ac motor speed is directly related to the frequency of the motor currents, and speed control requires a variable frequency voltage source. Maximum efficiency is achieved when there is maximum rotor stator field misalignment. Motor efficiency also depends on motor construction and particularly the rotor field structure. In asynchronous induction motors (AIM), current flows in both rotor and stator winding and some minimum stator current is consumed in magnetizing the core. Permanent magnet synchronous motors (PMSM) are more efficient because they do not require any current to magnetize the rotor field. Ultrahigh efficiency interior permanent magnet (IPM) motors generate additional torque by virtue of their salient magnetic core structure.
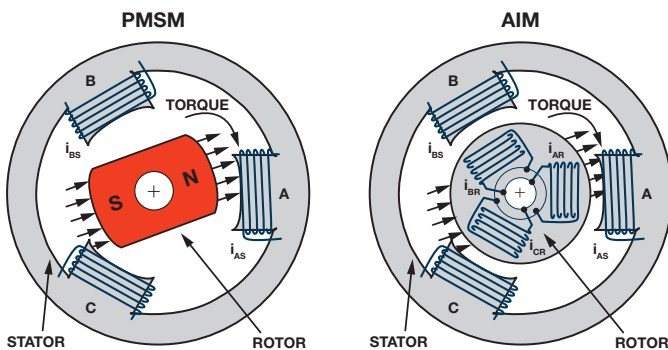

Figure 2. PMSM and AIM motors have similar stators but very different rotor field structures.

All of the above motors are used in industry, depending on power and application requirements, but the asynchronous induction motor is by far the most common by virtue of its simple construction and ease of use. Permanent magnet synchronous motors have a higher torque to weight ratio and the low inertia rotor structure makes it very suitable for high dynamic control in automation equipment. However, the AIM can be started when connected directly to a 3-phase ac line and speed can be controlled using a simple frequency inverter. Before the present day focus on efficiency, it was typical to connect a fan, pump, or compressor motor directly to the ac line and control the process using dampers, valves, or a simple on/off control. Open-loop frequency control drops the power consumption of a centrifugal pump to less than 20% of full power when running at 50% speed, while consumption is 50% of full power using an on/off control to reduce flow rate to 50%. The availability of such gains in system efficiencies encourage factory operators to retrofit inverters to existing fixed speed motor applications. These days, advanced algorithms can tune the stator voltage to regulate the rotor field and to optimize efficiency. Drive manufacturers now supply standard drive boxes that can be configured for a variety of motor models and types. The latest analog and digital signal processing devices enable the introduction of advanced control to even cost sensitive inverter applications. Estimation algorithms calculate the angular position of the rotor field from stator current and voltage measurements alone. These sensorless control algorithms ease the adoption of highly efficient IPM motors to maximize process efficiency in applications such as compressors and conveyers. Higher power applications, such as winding machines or large pumps, still tend to use induction motors, but the typical efficiency of 500 kW motor can be as high as 96%.

These drives typically include algorithms to optimize motor efficiency and monitor drive health. Traditionally, these drives have serial field bus connections that allow operational and diagnostic data to be logged by a local PLC. A growing trend is to connect the drives to the factory network using industrial Ethernet protocols such as Ethernet/IP or Modbus TCP to improve efficiency by coordinating the operation of multiple drives.

Efficient Motion Control: Precision Isolation and Communications

The combination of precision in motion control and communication timing enables shorter machine production cycles and reduces the amount of energy consumed to manufacture each part. This is critical in automation systems where machine productivity and quality often has a higher weighting than the motor energy efficiency because of the capital invested in the equipment. Drive manufactures support automation applications with PMSM service motors and drives designed for fast response and high precision in the speed and position control. A fast control processor coupled with precision voltage drive and current feedback delivers smooth dynamic torque control. The high voltages and currents in the power inverter presents a challenge to the circuit designer because the isolation circuits must meet stringent electrical safety standards. High speed magnetic isolation technology supports safe isolation of analog and digital signal voltages without compromising speed or precision. Precision analog-to-digital converters embedded in the encoder position provide up to a 24-bit resolution position feedback, which enables high dynamic velocity control at speeds as low as 1 RPM. This performance level supports automation applications such as multiaxis milling of precision machine parts, assembly of fine geometry integrated circuits, or injection molding of cell phone parts. In addition to control precision, the motion timing of the motors needs to be tightly synchronized since a timing error translates directly into a trajectory error in multiaxis position control. Synchronized industrial Ethernet protocols, such as PROFINET and EtherCat use modified Ethernet network interfaces to support real-time synchronization of data with clock jitter as low as 1 μs. These network interfaces support both synchronized motion control for production efficiency and factory network connectivity for production system management.

Engineering Efficiency: Rapid Customization

Modeling tools enable drive companies to quickly customize control algorithms for end applications without significant investment in trial and error tuning on the factory floor.

Automated machines are complex interconnected systems requiring the support of multidisciplinary engineering teams. Figure 3 illustrates just some of the key design functions needed to support the development of automation equipment. Typically, many of these engineers work in different companies and so the various suppliers in the chain must support designers performing the integration work. Modeling tools from companies like MathWorks support complete system models, including state control, motion algorithm, motor, and machine load. Specialized electromagnetic and mechanical design tools generate behavioral models of the ac motor and the machine, increasing the accuracy of system models. While the complete design process cannot be fully automated, the number of prototype builds can be significantly reduced. The control algorithm for a new motor or machine can be developed and tested on a simulation platform before prototypes are built. Automatic code generation tools allow rapid deployment of the control algorithm on the test platform. Each design iteration provides new data to improve the accuracy of the system model. Automatically generated control code combined with proven system application code can be used in the production drive system. Drive companies can thus rapidly deploy new control functions optimized for specific applications to optimize energy efficiency and automation productivity.
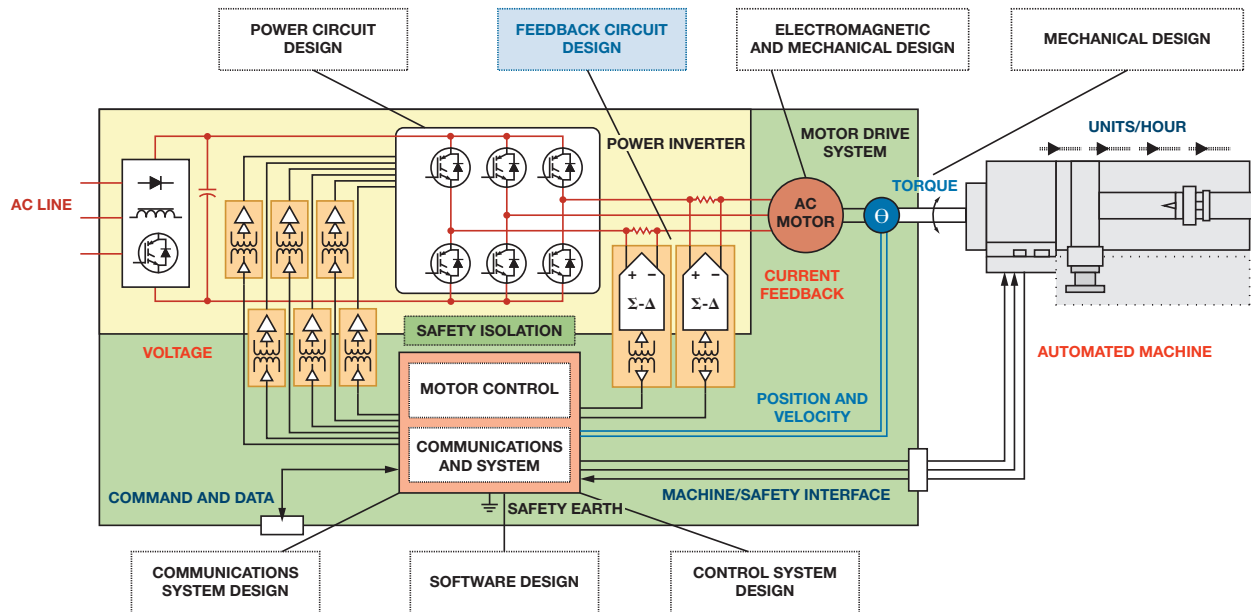
Figure 3. A wide variety of engineering tools are needed to support motor drive and automation system designs.

Conclusion

More and more industrial and instrumentation applications require precision converters to accurately control and measure various processes. Additionally, these end applications are demanding increased flexibility, reliability, and feature sets, while simultaneously reducing costs and board area. Component manufacturers are addressing these challenges and offering a number of products to address the needs of system designers for current and future designs. As can be seen from this article there are many different approaches in selecting the right components for precision applications, each offering their own associated drawbacks and benefits. As the accuracy of the systems increases, additional thought needs to be put into the selection of the right component to suit the application needs.

For more information on any of the above mentioned products visit *www.analog.com/motorcontrol*.

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References

[1] Conrad U. Brunner and Paul Waide. "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems." International Energy Agency working paper, 2011.

[2] EUREL Task Force. "Electrical Power Vision 2040." EUREL General Secretariat, February 2013.

Note: units for CO_2 emissions are Mt where 1 t = 1000 kg.

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Analog Devices, Inc.
Worldwide Headquarters
Analog Devices, Inc.
One Technology Way
P.O. Box 9106
Norwood, MA 02062-9106
U.S.A.
Tel: 781.329.4700
(800.262.5643,
U.S.A. only)
Fax: 781.461.3113

Analog Devices, Inc.
Europe Headquarters
Analog Devices, Inc.
Wilhelm-Wagenfeld-Str. 6
80807 Munich
Germany
Tel: 49.89.76903.0
Fax: 49.89.76903.157

Analog Devices, Inc.
Japan Headquarters
Analog Devices, KK
New Pier Takeshiba
South Tower Building
1-16-1 Kaigan, Minato-ku,
Tokyo, 105-6891
Japan
Tel: 813.5402.8200
Fax: 813.5402.1064

Analog Devices, Inc.
Asia Pacific Headquarters
Analog Devices
5F, Sandhill Plaza
2290 Zuchongzhi Road
Zhangjiang Hi-Tech Park
Pudong New District
Shanghai, China 201203
Tel: 86.21.2320.8000
Fax: 86.21.2320.8222

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