SENSORLESS VERSIONS OF THESE HIGHLY EFFICIENT MOTORS REDUCE COST AND PARTS COUNT, BUT THE MOTORS STILL REQUIRE COMPLEX CONTROL ALGORITHMS. MATCH THE RIGHT MOTOR TYPE AND CONTROLLER TO YOUR APPLICATION FOR THE BEST PERFORMANCE AND COST.

PERMANENT-MAGNET MOTORS boost efficiency and power density

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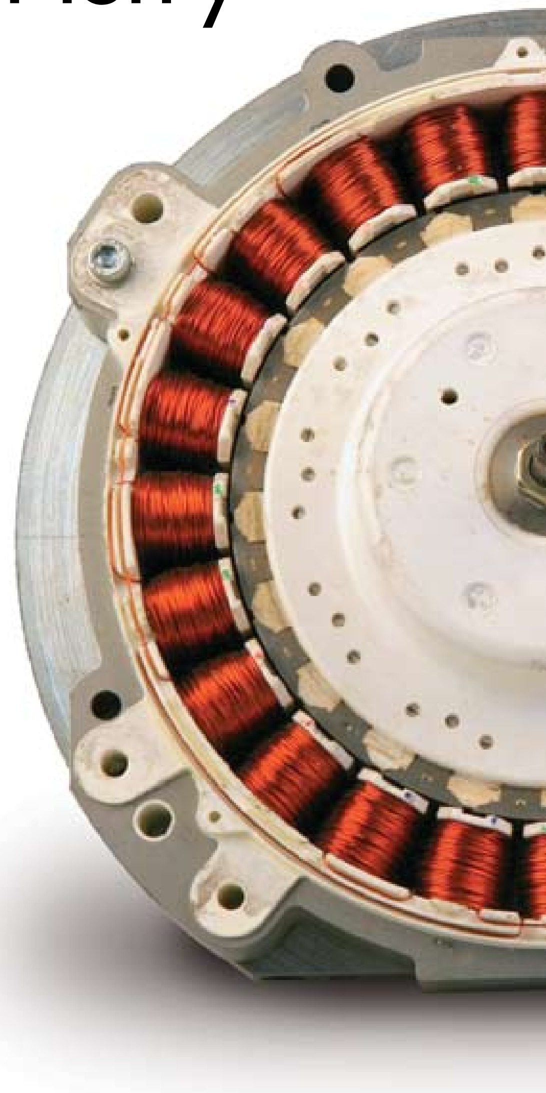

The global price of energy is at an all-time high, with few signs of relief in sight, making consumers and businesses alike interested in energy conservation. Currently, the most common motor type in use is the single-phase ACIM (ac-induction motor), which is efficient only while running at a constant speed, though most applications—whether in the home or in industry—run at variable speeds. Worse, applications with a reverse speed, such as washing machines, require gearboxes, which reduce power density as well as efficiency. For high-power applications, using ACIMs is still the rule, but, at 2 kW and less, permanent-magnet motors are taking over in new designs. (As a reference, a washing-machine motor uses about 1 kW or less.)

Permanent-magnet motors have been commercially available since the '90s but didn't initially see widespread use because of the high cost that they owe to the expensive permanent magnets on their rotor. In addition, their complex control algorithms require specialized engineering expertise as well as the additional expense of an embedded processor (see **sidebar** "How permanent-magnet motors work" at the Web version of this article at www.edn.com/070913df).

Recently, however, the price of copper, which both the stator and the rotor windings of ACIMs use, has risen. These prices have had less impact on permanent-magnet motors, which lack rotor windings. At the same time, permanent-magnet prices have dropped.

At their most basic, permanent-magnet motors require some kind of sensor—usually, a Hall-effect type—to determine the position of the rotor with respect to the windings on the stator. The motor's control-drive electronics use the rotor-position feedback to adjust the pulse-width-modulated drive signals to the windings. However, using sensors is not the only way for the control electronics to monitor position: Motor-control processors have become more powerful and can now calculate rotor position from the motor's back EMF (electromotive force), eliminating the need for position sensors for some applications (**Figure 1**). For example, new designs for hermetically sealed refrigeration compressors are moving to permanent-magnet motors for higher power efficiency. Formerly, they relied on single-phase ACIMs, which required just two electrical connections through the hermetic seal. It's not a big leap for the designs to bring out one more line for a three-phase permanent-magnet motor drive, but bringing out three additional position-sensor lines through the hermetic seal would be too expensive and decrease reliability. Sensorless permanent-magnet motors are better options.

However, sensorless permanent-magnet motors are not the answers for all applications. The rotor must be moving at some minimum speed to generate a back EMF, which sensing requires. These devices are good only for motors in applications whose operating speed ranges from 5 to 100% of the top speed. In addition, applications requiring precise positioning usually require sensored motors. But, for applications such as consumer appliances and many industrial-control systems, sensorless permanent-magnet motors are making significant inroads.

There are two kinds of permanent-magnet motors: brushless-dc motors and PMSMs (permanent-magnet synchronous motors). Brushless-dc-motor windings give a trapezoidal back EMF and respond to a trapezoidal-drive signal (**Figure 2a**); PMSMs produce a sinusoidal back EMF and require a sinusoidal-drive signal (**Figure 2b**). Their different drive signals and, thus, their torque make for a key difference in the drive characteristics of the two motors: The brushless-dc motor is subject to torque ripple of approximately 13%, and the PMSM theoretically has 0% torque ripple.

AT A GLANCE

- Permanent-magnet motors are more efficient than ac-induction motors, but they require more sophisticated control circuitry.
- Sensorless permanent-magnet motors are less expensive and more reliable than those with sensors, but some applications that require less-than-5%-of-maximum speed or frequent stops and starts require sensors.
- Microcontroller, DSC (digital-signal-controller), and semiconductor vendors are offering development platforms with control algorithms to ease the task of designing for these motors.

A six-step commutation process drives brushless-dc motors. As the process applies the drive voltage between two phases of the windings, the third phase senses the back EMF. The sequence to drive the rotor takes six steps; hence, manufacturers often call this sequence a six-step process. This algorithm is relatively straightforward, and you can implement it with an 8-bit processor or with an 8-bit processor and a hardware-based coprocessor. Freescale, Infineon, Microchip, STMicroelectronics, and Texas Instruments have developed the software for the six-step commutation algorithms for their microcontrollers and DSCs (digital-signal controllers), which are, in general, 8-bit devices.

FOC HELPS PMSMs

However, brushless-dc motors have drawbacks that make them unsuitable for some applications. For example, the dynamic response of trapezoidal control isn't optimal for washing machines, because the load changes both dynamically within a wash cycle and varies from load to load and selected wash cycle. Further, in a front-loading machine, the gravitational power works against the motor load when the load is on the top side of the drum. The sinusoidally driven PMSM with FOC (field-oriented control) can better handle dynamic-load changes, but it requires a more powerful processor to handle the vector computations (**Reference 1**).

FOC relies on two algorithms: The Clarke algorithm converts the stator-winding-phase currents from a three-axis vector to a two-axis vector, referenced to the stator. The Park transform then converts the two-axis currents into a rotating system, still relative to the rotor. Clearly, the computational power these transformations require is both complex and computationally inten-

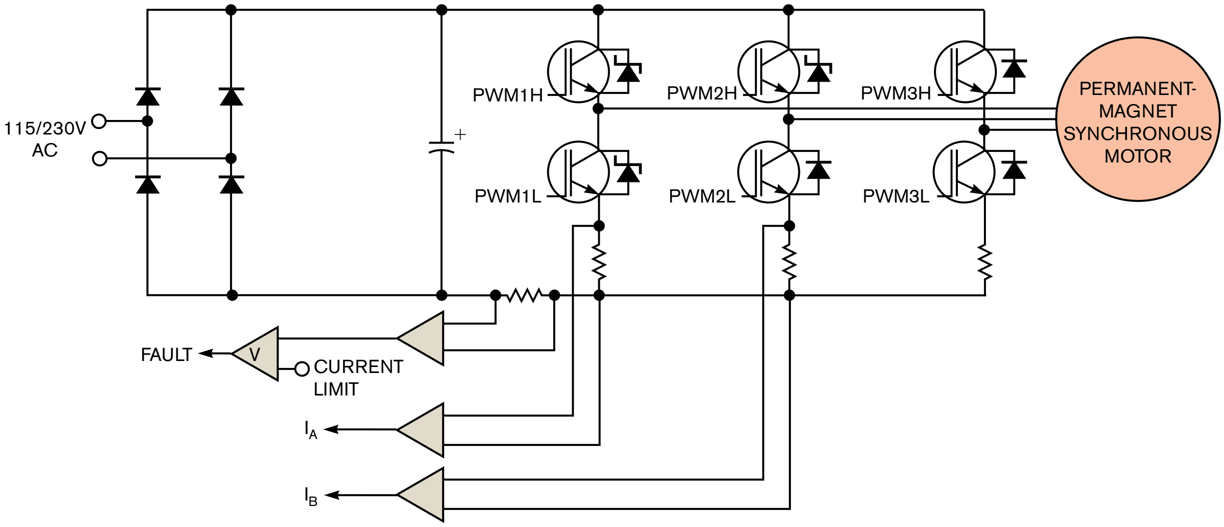

Figure 1 A three-phase permanent-magnet motor requires a processor to create the control algorithms for the inverter to drive the motor's windings. The six high and low PWM signals come from the motor-control processor. A sensorless permanent-magnet motor relies on the motor's back EMF to sense the rotor position and control the motor direction and speed. The processor uses currents I_A and I_B to calculate back EMF.

sive. Several microcontroller and DSC vendors offer development platforms for their chips that they tailor to run these algorithms. Microchip offers the 16-bit dsPIC33FJ12MC201/203 DSC, which includes a PWM with two independent clock sources for advanced motor-control algorithms and active power-factor correction, as well as a user-selectable 1.1M-sample/sec, 10-bit ADC or 500k-sample/sec, 12-bit ADC. The DSC can operate at 40 MIPS, and the Clarke and Park algorithms require 11-MIPS performance, leaving 72% of the DSC's overhead for performing other tasks, such as computing power-factor control. The chips sell for $1.99 (volume quantities).

You can perform FOC-vector calculations with Infineon's 8-bit XC886/88 processor, which includes a CORDIC (coordinate-rotational-digital computer) to perform hard-coded trigonometric functions necessary for the Clarke and Park routines before transferring the result to the chip's general-purpose controller, which interfaces with the drive circuitry. The company offers FOC-software algorithms for the 8-bit processor that take up 58% of the CPU's performance. So, depending on what other chores your processor has, this amount of processing power could be enough. The 8-bit version sells for $2 to $3, depending on volume. Infineon plans to introduce a 16-bit version in October.

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- For a PowerSource blog post on algorithms and motor efficiency, see "As motors go green, free code helps to further reduce price," www.edn.com/070913df2.
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These motor-controller engines all come from companies that are in the microcontroller business. These companies offer the algorithms in software that you can modify for performance in an application. International Rectifier's approach differs from these companies in that its iMotion platform implements the control algorithms in hardware, resulting in the usual hardware-versus-software-algorithm trade-off: The hardware algorithms run fast—with a typical FOC calculation taking just 11 μsec in the iMotion digital-control engine—but you can't modify them.

Freescale has teamed with Fairchild and Nidec Shibaura to make a package of Freescale's 56F800/E DSC family, Fairchild's switching-power semiconductors, and Nidec Shibaura's flat, round "pancake" PMSM; the initial products target washing machines. Freescale provides the sinusoidal-control algorithms for the motor controller, and Fairchild provides the high-power-semiconductor switches for the inverter-drive electronics. Nidec Shibaura's pancake motor tunes the DSC, inverter, and motor all to work with each other for the washing-machine application.

WATCH YOUR HEAD ROOM

Cliff Ortmeyer, market-development manager in the appliance sector for STMicroelectronics, says that the 8-bit ST7MC1/2 processor dedicates a motor control to peripherals and works well for brushless-dc-motor control and the six-step control process. But he says that you need a more powerful 32-bit processor for the FOC of PMSMs. He agrees that it's vital to have adequate processing power in the controller to handle not only the vector computations, but also other system-control functions. "Our [PMSM-control] designs use less than 50% of the CPU to perform the main motor control. So, with the 32-bit ARM7/9 processor, that leaves a huge amount of power for the other application functions."

The price decreases and new technology for PMSMs make them inviting devices to employ, but they may not

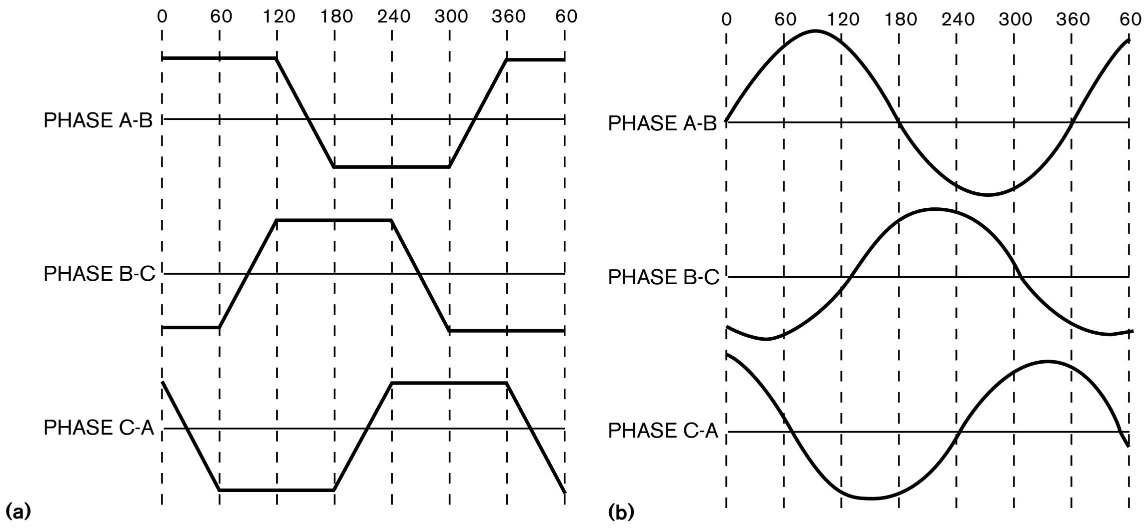

Figure 2 A trapezoidal-drive current in a six-step process drives a brushless-dc motor, possibly resulting in a torque ripple of as much as 13% (a). The motor-drive current to a PMSM is sinusoidal, giving an ideal torque ripple of zero, but the trade-off is that the control algorithm is more complex (b).

be the best devices for your application. Even though STMicro makes controllers for both motor types, Ortmeyer suggests that you not dismiss a brushless-dc motor for your application just because PMSMs are getting all the attention now. Brushless-dc motors can use a simpler controller, and simple is always a good idea. So, how do you decide on the best motor type? Ortmeyer says that you should consider whether your application needs to use the motor for regenerative braking and whether it needs to reverse direction. For example, a washing machine needs to reverse, but it doesn't need to use the motor for braking. If you need both capabilities, you should choose a PMSM and sinusoidal control. If you need to do only reverse speed or braking, then you may well be able to get by with a brushless-dc motor and its simpler controller.

When you're determining the processing power you need, you should consider the overall system needs of your application—not just the algorithm-crunching part of motor control. Arefeen Mohammed, systems application engineer for Texas Instruments' C2000 DSC line, says that, five years ago, no one would consider using a 32-bit processor for an appliance-motor-control application, such as a washing machine. However, front-loading washing machines have a complex performance profile: The horizontal position makes them more efficiently use water but comes with a correspondingly more complex motor controller. "Now, you'll use the processor not just for motor control, but also to sense water level and temperature." He suggests you look at the overall system efficiency and not just the motor.

"Five years ago, a representative microcontroller for motor control had a 10-bit ADC with a total conversion time of about 5 μsec. Now, we offer a 12-bit ADC with a total conversion time of about 80 nsec, and we are receiving the requests to improve further. So, right now, 12 bits is a kind of standard. For advanced high-performance motor drives, we are already seeing the need for 16-bit ADCs," says Mohammed.**EDN**

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www.nidec-shibaura.com

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HOW PERMANENT-MAGNET MOTORS WORK

Permanent-magnet motors rotate because of the torque that the interaction of two magnetic fields causes: the field that the permanent magnets mounted on the rotating rotor create and the magnetic field that the stationary windings of the stator induce. The torque is greatest when the magnetic vector of the rotor is at 90° to the magnetic vector of the stator, because it forces the poles of the rotor to rotate in the direction of the stator field. In a trapezoidally driven brushless-dc motor, a current flow alternating sequentiallly through two of the three coils generates the stator field. The remaining third coil monitors the back EMF (electromotive force) of the two active coils (Figure A).

Back EMF occurs when a permanent-magnet motor rotates, and each winding generates a voltage that opposes the main voltage to the windings. Back EMF depends on the angular velocity of the rotor, the magnetic field that the rotor magnets generate, and the number of turns in the stator windings. The motor's back EMF provides the feedback of the rotor's position with respect to the stator windings; permanent-magnet motors with sensors–usually, Hall-effect sensors–provide a similar position feedback. The stator magnetic vector is almost always misaligned with the rotor, causing a ripple in the torque. Torque ripple can cause increased mechanical wear, vibration, and noise, and it generally degrades motor performance.

With sinusoidal commutation, which PMSMs (permanent-magnet synchronous motors) use, the drive-control circuitry simultaneously powers the three coils. Figure B illustrates the vectors at sinusoidal commutation. The sinusoidal-drive currents in the three coils are phase-shifted by 120°, and the force smoothly rotates, with the stator vector remaining at a 90° angle from the rotor vector. An ideal motor with a sinusoidal drive shows torque ripple (Reference A).

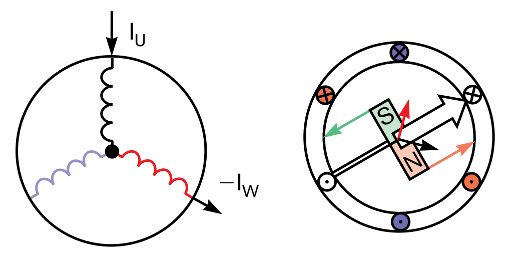

Figure A In a six-step commutation algorithm, the control electronics apply current to just two of the three stator coils at a time and monitor the back EMF through the third coil. The purple and red arrows represent the magnetic field that the stator coils cause, and the white arrow is the resulting stator field. The magnetic dipole represents the rotor's permanent magnets' field, and the light red and green arrows at the poles represent the rotor torque.

REFERENCE

A "XC886/888 CM/CLM Sensorless Field Oriented Control for PMSM Motors," AP08059 Application Note V.1, Infineon, May 2007, www.infineon.com/dgdl/AP0805910_Sensorless_FOC.pdf?folderId=db3a3043134aa0ee01134dcf16670067&fileId=db3a3043134dde6001134e2c3cff002f.

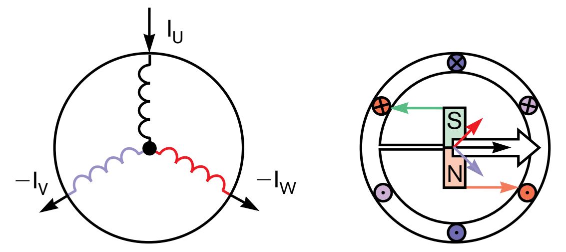

Figure B With sinusoidal commutation, the motor-control electronics apply sinusoidal currents phase-shifted by 120° to the three coils simultaneously. As a result, the force that the electromagnetic-space vector creates is smoothly rotated along, so that the stator vector remains at a 90° angle from the rotor vector.