DSPs excel in motor-control applications

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By using a DSP for electric motor control, you can expect lower costs, better reliability, and less energy consumption.

Motor control is a new application for DSPs that takes full advantage of the devices' number-crunching power. Billions of new electric motors are responsible for an estimated 70% of worldwide consumption of electric power. Thus, designers are enthusiastically turning to DSPs to improve the control efficiency of electric motors. DSPs implement sensorless control, which calculates velocity and position in real time from known current and voltage values, and field-oriented control, which converts all variables to a coordinate system relative to the magnetic field of the rotor.

The prices of DSPs have dropped from hundreds of dollars to approximately three dollars since their introduction in the early 1980s. Performance of 16-bit DSPs has increased from 5 to nearly 2000 MIPS. A few thousand words of on-chip memory is no longer the only peripheral you can integrate onto the DSP. Instead, DSPs can now integrate a variety of sophisticated peripheral features that make them applicable across a spectrum of industries and products.

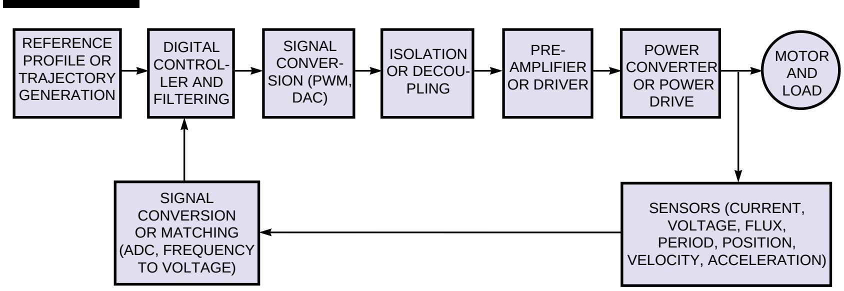
Electric motors are either brush or brushless machines. Brush machines are dc-brush motors. Brushless machines are ac-induction, dc-brushless, or switched-reluctance motors (SRMs). Before the existence of DSP motor control, designers' rule of thumb dictated using either expensive dc-brush motors with cheap controllers or cheap ac-brushless motors with complex, expensive controllers. Complex variable-speed controller designs for ac-induction motors, dc-brushless motors, and SRMs must contend with cross-coupled torque and speed controls. These motors are nonlinear and require more sophisticated control methods to achieve levels of performance similar to those of dc-brush motors. Thus, although dc-brush motors generally require more maintenance than ac- and dc-brushless motors, simple linear-control structures, such as independent control of the excitation field and torque, previously made dc-brush motors the choice for most control applications. However, DSP motor control changes the rule of thumb by enabling low-cost implementations of complex controllers for brushless motors.

Achieving acceptable levels of control for ac and brushless motors requires advanced control techniques. These techniques require computational speeds beyond the means of most µCs. Also, the high cost of control systems remains a primary concern and precludes the use of fast RISC or CISC µPs. Brushless motors are the option for products that need to be more efficient, cheaper, quieter, and more reliable. These motors range from small linear-stepping motors to medium dc-brushless motors to large induction motors.

The most common ac-brushless motors furnish precise torque control and speed regulation, render excellent response to rapid speed or load changes, and provide low weight and energy efficiency. To cost-effectively employ these new motors, engineers have developed innovative control systems that require no massive support circuitry.

A digital-control system generally includes a set of system-response specifications (a transfer function), a controlled process, a computational element (CPU), sensors to measure the system's variable physical parameters, ADCs, and DACs (**Figure 1**). The computational element must be fast enough to complete the execution of the control-transfer-function algorithm before the end of the sample frame. A controller's

FIGURE 1



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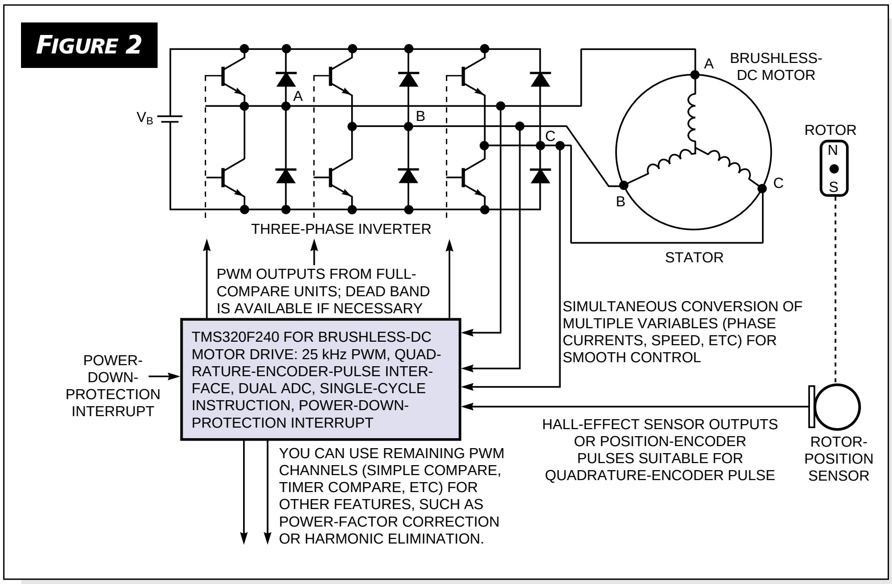
sampling rate typically must be 10 to 20 times the bandwidth of the system under control. In practice, high-end motion-control applications require a processor that executes 8 to 20 MIPS per control axis. Increasingly, the options for modern motor control are shifting away from underpowered µCs to DSPs. DSP manufacturers are introducing application-targeted DSPs that suit the needs of the motor-control market.

Today's 16-bit DSPs deliver far better performance-to-price ratios than the 16-bit µCs that traditionally make up the high end of digital control. The advantages of a DSP or DSP core are single-cycle multiplication and result accumulation, which result in improved performance. For example, TI's TMS320F240, a 16 bit, fixed-point DSP, is optimized for motor-control functions (**Figure 2**). The chip incorporates a 20 MIPS processor, two 10-bit ADCs, and specialized "event-manager" circuitry for controller applications. As a dual-bus, Harvard-architecture machine, the TMS320F240 simultaneously fetches a data operand and an instruction in one cycle. This feature alone provides the DSP with at least double the speed of an equivalent µC.

FIGURE 2



A brushless-dc-motor drive uses the TMS320F240 DSP.

DSP-control tasks

Although early control-system applications used DSPs to implement classic digital-controller algorithms, designers now incorporate control functions into one DSP. Thus, DSPs can now handle all tasks in a digital-control system (**Figure 3**). For example, a DSP uses additional processing of input and feedback signals from motor sensors to improve noisy or inaccurate signals. This feature eliminates the need for costly, heavy, or unreliable sensors. This processing also improves overall sensor operation, thereby achieving a "smart sensor." A smart sensor is inexpensive, lightweight, and reliable and is usually closely associated with a DSP or µP. Because a DSP can use sophisticated algorithms to process sensed variables and generate a valid estimate for nonsensed variables, such as rotor position and flux, sensorless control is an attainable goal for some applications.

Microprocessor-control applications frequently rely on approximate-value look-up tables to generate control inputs. DSPs can effectively replace these tables and their interpolation processes with a function or an algorithm executed on the fly. This feature permits more complex multivariable functions, reduces memory demands, and provides more options. In addition, system operations using algorithms rather than table-look-up processes are generally smoother, thereby reducing mechanical resonance excitation and power consumption and improving the reliability of drivers and motors.

DSPs also allow real-time implementation of advanced algorithms to improve system control. A sufficiently powerful DSP can implement single- or multiple-axis control systems. Many control methods, including adaptive and optimal multivariable control, dual control, learning, self-tuning, neural networks, genetic algorithms, and fuzzy logic, exploit DSP speed and performance.

In many control systems, you must estimate some system parameters or the system model before or during normal operation. DSP performance offers enough spare processing power to include an identification process or parameter estimations along with other DSP tasks.

Many digital-motor-control systems require power-supply signal conditioning and power-factor correction (PFC). Control systems, especially those using electric motors, frequently control switching-power converters with PWM. DSPs often carry out PWM generation and electronic commutation of ac motors. PWM eliminates DACs, thereby reducing component count, power dissipation, and motor-drive-system size. Advanced methods, such as space-vector PWM, use DSPs to execute intensive calculations within a few microseconds. These methods improve efficiency and usage of supply voltages and eliminate undesired harmonics in motor currents, thereby improving the condition of the signal, or power quality.

DSPs can easily handle the diagnostics and safety supervision of system operation, which constitute most of the processing that a practical control system performs. In many control systems, DSPs also handle other noncontrol-system tasks, including communication with the host computer, data filtering, and data-bus control protocol (SCSI, for example).

More than ever before, control and reduction of system noise are important to designers, manufacturers, and end users. Achieving these goals requires attenuation of mechanical vibrations and of acoustic, signal-harmonic, and mea-

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surement noise. By using active advanced algorithms that require additional computational power, today's DSPs perform these tasks at almost no cost penalty.

With ac motors, you can connect directly to a control load without a hydraulic subsystem, because the DSP allows fast and precise variable-speed or torque control. This feature is advantageous in automobiles, in which hydraulic systems take up valuable space and waste 5% or more engine power. For example, consider a power-steering system. By programming a DSP to control the electronic system, you not only save space, power, and cost, but also get rapid behavior response and more flexibility. Other automotive applications in which the adaptive-control features of the DSP chip are useful include antilock-brake control at each wheel, smooth drive-train-torque control in automatic transmissions, and motorized active-suspension control.

Uses for and benefits of ac-brushless motors proliferate not only in the automotive industry, but also in the consumer white-goods market (in appliances such as washers and dryers), office-supply manufacturing, and heating and air conditioning. For example, DSPs can control blower and compressor motors for reduced power consumption and quieter operation. It is also easier to program motors in these appliances for soft starts to minimize vibration, noise, and wear. Manufacturers of office products, such as printers, copiers, and tape drives, also use DSP motor control to realize lower manufacturing costs and quieter, more reliable products.

Math-intensive algorithms

You can use ac motors in these and similar applications because DSPs can mathematically execute intensive control algorithms. These real-time algorithms use a variety of input signals from motors, including phase currents, voltages, flux (rotor or stator), rotor position, rotor speed, and rotor temperature to generate the required output control signals.

One of the most efficient ways to control an ac-brushless motor is with field-oriented control. Field-oriented control provides excellent dynamic-control behavior by converting all variables to a coordinate system relative to the "rotor flux," or the rotor's magnetic field. This control method uses the current component that is parallel to the rotor flux to hold the flux constant and controls the motor torque by the orthogonal current component.

Field-oriented control requires powerful arithmetic-processing capabilities to calculate the rotor flux and perform the necessary coordinate transformations of variables from the stator frame of reference to the rotor-flux frame of reference. The DSP must perform a real-time conversion from field coordinates to stator coordinates and vice versa during each controlling cycle. DSPs such as the TMS320F240 have the computational power required to perform these operations in microseconds.

Sensorless control is another aspect of motor control in which math-intensive calculations require DSP chips. Although mechanical devices for sensing position and velocity supply the input variables for motor-control circuits, providing such sensors is often technically difficult or expensive. For example, pumps used to extract oil from deep beneath the sea would need long and expensive cables to transmit sensor data to the surface. The alternative is a DSP-based mathematical option that calculates velocity and position in real time from known current and voltage values. This option eliminates the need for sensors. DSP-based sensorless control reduces system size and cost and is rapidly spreading beyond industrial use to such areas as white goods.

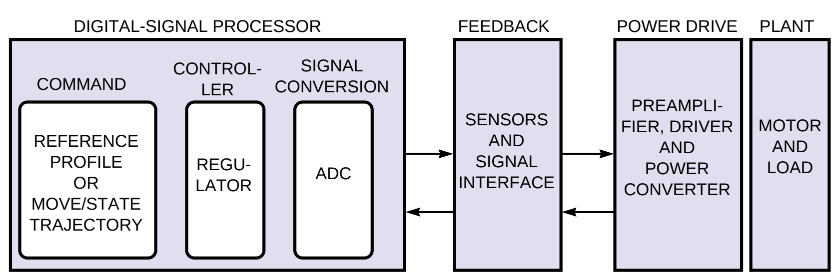
DSPs monitor and control a system by processing dynamic-control algorithms, which sense variations in system behavior and send out signals to modify this behavior in real time. For example, DSPs can rapidly execute FFT algorithms. Therefore, the motor controller can perform spectrum analysis on mechanical vibrations in real time, enabling constant diagnostic monitoring of motor performance to predict and prevent system failure. DSPs can also easily implement sharp cutoff notch filters that eliminate narrowband mechanical resonances that would otherwise dissipate energy and possibly cause system instability.

Control for ac-induction motors

Electronically controlled, variable-speed, ac-induction motors now compete with dc-brush and -brushless motors for cost and performance efficiency in many applications. This situation is the result of technological advancement in power electronics and especially in DSPs. Applications range from robotics and numerically controlled machine tools to railway traction, ship propulsion, and rolling mills. Emerging applications include heating, ventilation, and air conditioning; fans and blowers; and refrigeration appliances.

Field-oriented control provides efficiency, optimal transient control, and steady-state control for ac-induction motor control. High efficiency requires a digital motor controller that accurately controls both the magnitude and the frequency of the inputs to an ac motor. In addition, when transient response is important, field-oriented control accurately controls transient torque and speed of the motor. Also, when you use sensorless control for an ac-induction-motor

FIGURE 3

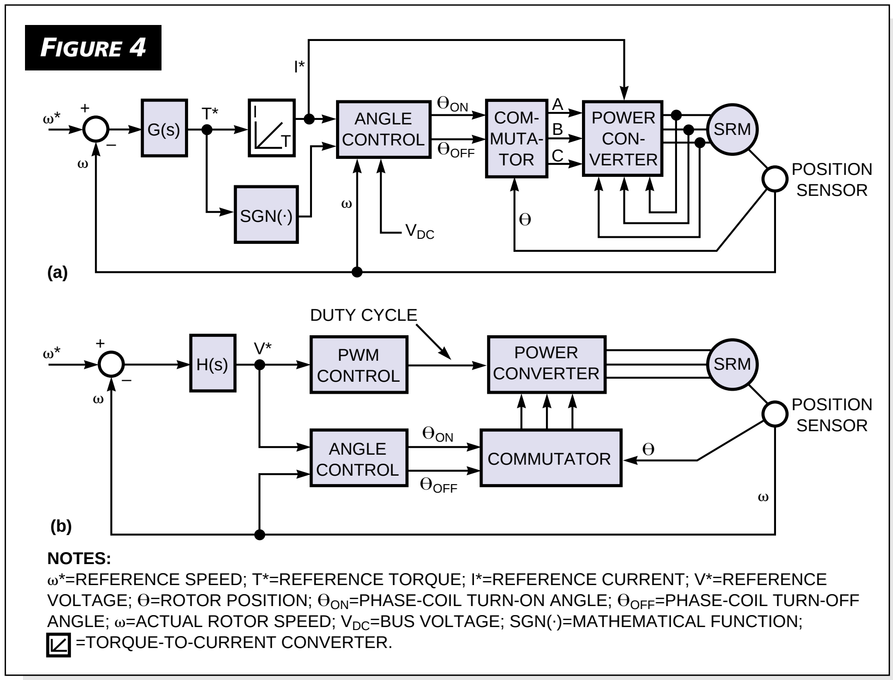


DSPs can handle all tasks in a digital-control system.

drive, you can eliminate position and speed sensors to save cost. For sensorless control, the computation-intensive estimation algorithms performed on available measurements use the DSP's processing bandwidth. Advanced motor-control methods, such as those based on adaptive control in which control signals adapt depending on the stimulus to the sensors, also require the math power of a DSP.

DSP control also helps efficiency in dc-brushless motors. The popularity of three-phase, dc-brushless motors is on the rise. These motors have no brushes to wear out or to arc over, and heat dissipation is lower because the motors' windings are on the stator. In addition, dc-brushless motors can achieve relatively good torque control with the availability of required electronic circuits. Control of the dc-brushless motor, however, requires a three-phase power inverter, a PWM current-control circuit, a Hall logic decoder, current-loop control, and protection circuitry.

FIGURE 4



Switched-reluctance-motor control is either current- (a) or voltage-controlled (b).

A three-phase brushless-dc motor has two, four, or more permanent magnet poles mounted on its rotor. The stator's stationary windings produce the required rotating field, whose three phases the controller needs to commutate in the proper sequence. The rotor's angular position governs this sequence. Consequently, the controller requires some means to both sense and use this position information to generate the proper commutation sequence. You can use Hall-effect sensors mounted on the stator close to the rotor magnets or a position encoder to obtain rotor-position information. An electronic circuit decodes this information to control the phase currents in the proper direction and sequence.

The electronics controlling a brushless-dc-motor drive must always maintain proper phase-current levels. At high speed, the motor's back EMF (electromagnetomotive force) limits the phase currents, but at low speeds, the back EMF is zero at zero speed, and, therefore, some other electronic means, such as closing the current loop for the phase currents, holds the current. Therefore, a brushless-dc-motor-control system not only must provide phase-current information but also must generate PWM signals to maintain the proper current level. Moreover, in emergencies, the system should disable all PWM channels to avoid system failure. Again, the DSP provides all the computational resources to handle this complex set of real-time requirements.

Switched-reluctance-motor drive

Steady advances in power electronics have made SRM drive systems increasingly popular. SRMs demonstrate high efficiency over a wide operating range, require less sophisticated power-converter topology, need no rotor windings, and occupy less space. They are doubly salient, singly excited motors and have salient poles on both the stator and the rotor. The stator comprises simple concentric windings, and there are no windings, bars, or permanent magnets on the rotor. Connecting stator windings on diametrically opposite poles in series forms a single phase. By energizing a stator-pole pair, the corresponding rotor-pole pair moves toward the energized stator-pole pair to minimize the reluctance of the magnetic path. Thus, by energizing the consecutive stator phases in sequence, the motor can develop a constant torque in either direction of rotation.

For SRMs, the magnetic circuit's tendency to adopt a configuration of minimum reluctance develops the torque. Thus, moving the rotor poles inline with the stator poles and maximizing the inductance of the excited coils develop the torque. This inline position is "aligned." In the unaligned position, the torque is independent of the direction of current flow, allowing the use of unidirectional currents. This situation permits simplifying the electronics power-switching topology compared with those topologies required for other types of machines.

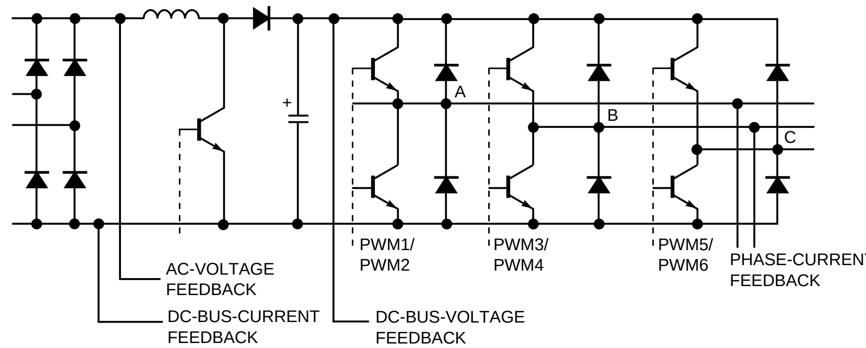
Constant current is supplied when $dL/d\Theta$ is positive for motoring and negative for generating. When this situation occurs, you achieve ideal current control. The important angles of the rotor position are Θ_o (turn-on angle, usually in the unaligned position), Θ_c (turn-off angle, usually a little before the aligned position), and Θ_q (current-extinction angle). Θ_D is the dwell (or conduction) angle, which is defined as Θ_c–Θ_o. If Θ_D is too large and $dL/d\Theta$ is negative, the current produces a negative, or braking, torque. Thus, carefully choosing Θ_D obtains maximum total torque. For PWM, or chopping, operation of the phase current, the turn-off angle, Θ_c, means you never apply negative voltage after Θ_c to the winding to reduce the current, and you never apply positive voltage again in the cycle.

SRMs are highly nonlinear machines. You develop the control system by considering the operating strategies of the machine over its torque-speed range. Use control modes, such as current or voltage control, phase advance, and dwell-angle control over the motor-speed range, to obtain the maximum motor performance for all operating conditions. Motor control is either current- or voltage-controlled (**Figure 4**). If the drive is torque-controlled, then the inner control loop must be a current-regulating controller.

The performance and operation of the reluctance motor depend on the accurate placement of the phase-current pulses relative to the machine rotor position. When the controller energizes a stator phase and the corresponding rotor-pole pair approaches the energized stator-pole pair, this position produces the motoring torque. Hence, you need information on the rotor position.

A DSP controller, such as TI's TMS320F240, fits the implementation of a switched-reluctance drive. Depending on the power converter and control algorithm, a four-phase SRM drive may need as many as six independent PWM channels. The TMS320F240 provides as many as nine independent PWM channels. Each channel provides independent control by writing compare values to their respective compare registers. Moreover, the device can close a digital current loop using the chip's dual ADCs and high-MIPS DSP core. Rotor-position information feeds directly to the TMS320F240 through its quadrature-encoder-pulse interface or through digital input pins. With a single-pin external interrupt, you can also disable all the PWM channels in case a fault condition occurs.

FIGURE 5



A three-phase voltage-source PWM inverter uses the TMS320F240's extra ADC and PWM channels to implement power-factor correction (PFC).

Power-factor correction

A three-phase voltage-source PWM inverter uses the TMS320F240's extra ADC and PWM channels to implement PFC (**Figure 5**). These features implement motor control, improve the condition of the power signal, and ensure fewer errors. The drive uses a boost converter to improve its input-power factor. At the least, proper implementation of this PFC circuit requires the ac-input voltage (rectified), the dc-bus current, and the dc-output voltage as feedback to the system. The controller processes these measured variables to obtain a suitable PWM pattern for the power device connected between the inverter dc bus. Implementing PFC along with a motor-control scheme reduces chip count by eliminating any dedicated PFC circuit or chip and increases the system's reliability. PFC also applies to the control of SRMs or induction-motor drives.

You can expect increasing demands for energy efficiency, system-cost reduction, and environmental consideration to consistently push the control-algorithm envelope. The evolution of higher performance DSPs with more dedicated peripherals makes DSPs the best engines for controlling motors and motion systems. Steady DSP improvements will enable sensorless, intelligent control and even further reduction of mechanical and hydraulic systems than are realizable today. EDN

Authors' biographies

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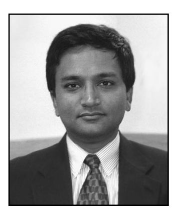

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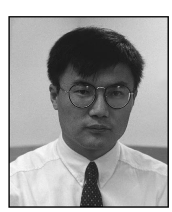

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