

# Fundamentals of DSP-Based Control for AC Machines

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## INTRODUCTION

High-performance servomotors are characterized by the need for smooth rotation down to stall, full control of torque at stall, and fast accelerations and decelerations. In the past, variable-speed drives employed predominantly dc motors because of their excellent controllability. However, modern high-performance motor drive systems are usually based on three-phase ac motors, such as the ac induction motor (ACIM) or the permanent-magnet synchronous motor (PMSM). These machines have supplanted the dc motor as the machine of choice for demanding servomotor applications because of their simple robust construction, low inertia, high output-power-to-weight ratios, and good performance at high speeds of rotation.

The principles of vector control are now well established for controlling these ac motors; and most modern high-performance drives now implement digital closed-loop current control. In such systems, the achievable closed-loop bandwidths are directly related to the rate at which the computationally intensive vector-control algorithms and associated vector rotations can be implemented in real time. Because of this computational burden, many high-performance drives now use digital signal processors (DSPs) to implement the embedded motor- and vector-control schemes. The inherent computational power of the DSP permits very fast cycle times and closed-loop current control bandwidths (between 2 and 4 kHz) to be achieved.

The complete current control scheme for these machines also requires a high-precision pulswidth modulation (PWM) voltage-generation scheme and high-resolution analog-to-digital (A/D) conversion (ADC) for measurement of the motor currents. In order to maintain smooth control of torque down to zero speed, rotor position feedback is essential for modern vector controllers. Therefore, many systems include rotor-position transducers, such as resolvers and incremental encoders. We describe here the fundamental principles behind the implementation of high-performance controllers (such as the ADMC401) for three-phase ac motors—combining an integrated DSP controller, with a powerful DSP core, flexible PWM generation, high-resolution A/D conversion, and an embedded encoder interface.

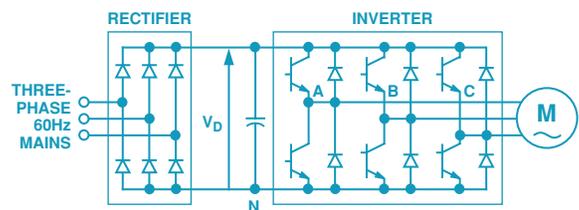
## VARIABLE SPEED CONTROL OF AC MACHINES

Efficient variable-speed control of three-phase ac machines requires the generation of a balanced three-phase set of variable voltages with variable frequency. The variable-frequency supply is typically produced by conversion from dc using power-semiconductor devices (typically MOSFETs or IGBTs) as solid-state switches. A commonly-used converter configuration is shown in Figure 1a. It

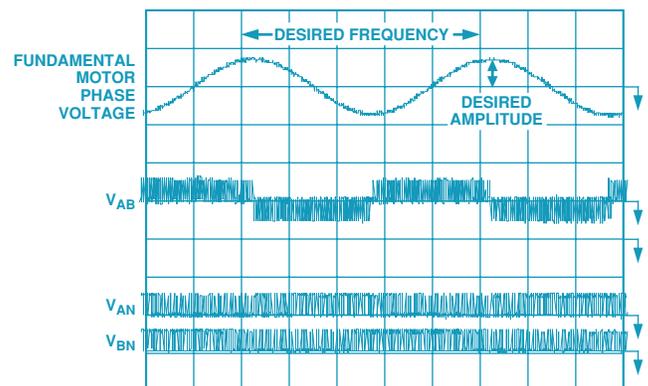
is a two-stage circuit, in which the fixed-frequency 50- or 60-Hz ac supply is first rectified to provide the dc link voltage,  $V_D$ , stored in the dc link capacitor. This voltage is then supplied to an inverter circuit that generates the variable-frequency ac power for the motor. The power switches in the inverter circuit permit the motor terminals to be connected to either  $V_D$  or ground. This mode of operation gives high efficiency because, ideally, the switch has zero loss in both the open and closed positions.

By rapid sequential opening and closing of the six switches (Figure 1a), a three-phase ac voltage with an average sinusoidal waveform can be synthesized at the output terminals. The actual output voltage waveform is a pulswidth modulated (PWM) high-frequency waveform, as shown in Figure 1b. In practical inverter circuits using solid-state switches, high-speed switching of about 20 kHz is possible, and sophisticated PWM waveforms can be generated with all voltage harmonic components at very high frequencies; well above the desired fundamental frequencies—nominally in the range of 0 Hz to 250 Hz.

The inductive reactance of the motor increases with frequency so that the higher-order harmonic currents are very small, and near-sinusoidal currents flow in the stator windings. The fundamental voltage and output frequency of the inverter, as indicated in Figure 1b, are adjusted by changing the PWM waveform using an appropriate controller. When controlling the fundamental output voltage, the PWM process inevitably modifies the harmonic content of the output voltage waveform. A proper choice of modulation strategy can minimize these harmonic voltages and their associated harmonic effects and high-frequency losses in the motor.



a. Typical configuration of power converter used to drive three-phase ac motors.



b. Typical PWM waveforms in the generation of a variable-voltage, variable-frequency supply for the motor.

Figure 1.

## PULSEWIDTH MODULATION (PWM) GENERATION

In typical ac motor-controller design, both hardware and software considerations are involved in the process of generating the PWM signals that are ultimately used to turn on or off the power devices in the three-phase inverter. In typical digital control environments, the controller generates a regularly timed interrupt at the PWM switching frequency (nominally 10 kHz to 20 kHz). In the interrupt service routine, the controller software computes new duty-cycle values for the PWM signals used to drive each of the three legs of the inverter. The computed duty cycles depend on both the *measured* state of the motor (torque and speed) and the *desired* operating state. The duty cycles are adjusted on a cycle-by-cycle basis in order to make the actual operating state of the motor follow the desired trajectory.

Once the desired duty cycle values have been computed by the processor, a dedicated hardware PWM generator is needed to ensure that the PWM signals are produced over the next PWM-and-controller cycle. The PWM generation unit typically consists of an appropriate number of timers and comparators that are capable of producing very accurately timed signals. Typically, 10-to-12 bit performance in the generation of the PWM timing waveforms is desirable. The PWM generation unit of the ADMC401 is capable of an edge resolution of 38.5 ns, corresponding to approximately 11.3 bits of resolution at a switching frequency of 10 kHz. Typical PWM signals produced by the dedicated PWM generation unit of the ADMC401 are shown in Figure 2, for inverter leg A. In the figure, AH is the signal used to drive the high-side power device of inverter leg A, and AL is used to drive the low-side power device. The duty cycle effectively adjusts the average voltage applied to the motor on a cycle-by-cycle basis to achieve the desired control objective.

In general, there is a small delay required between turning off one power device (say AL) and turning on the complementary power device (AH). This dead-time is required to ensure the device being turned off has sufficient time to regain its blocking capability before the other device is turned on. Otherwise a short circuit of the dc voltage could result. The PWM generation unit of the ADMC401 contains the necessary hardware for automatic dead-time insertion into the PWM signals.

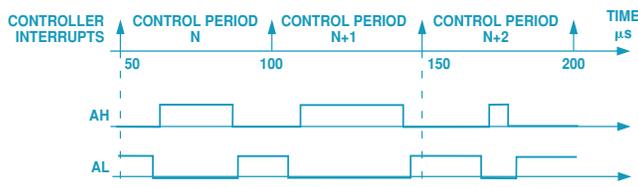


Figure 2. Typical PWM waveforms for a single inverter leg.

### General Structure of a Three-Phase AC Motor Controller

Accurate control of any motor-drive process may ultimately be reduced to the problem of accurate control of both the torque and speed of the motor. In general, motor speed is controlled directly by measuring the motor's speed or position using appropriate transducers, and torque is controlled indirectly by suitable control of the motor phase currents. Figure 3 shows a block diagram of a typical synchronous frame-current controller for a three-phase

motor. The figure also shows the proportioning of tasks between software code modules and the dedicated motor-control peripherals of a motor controller such as the ADMC401. The controller consists of two proportional-plus-integral-plus-differential (PID) current regulators that are used to control the motor current vector in a reference frame that rotates synchronously with the measured rotor position.

Sometimes it may be desirable to implement a decoupling between voltage and speed that removes the speed dependencies and associated axes cross coupling from the control loop. The reference voltage components are then synthesized on the inverter using a suitable pulsewidth-modulation strategy, such as *space vector modulation* (SVM). It is also possible to incorporate some compensation schemes to overcome the distorting effects of the inverter switching dead time, finite inverter device *on*-state voltages and dc-link voltage ripple.

The two components of the stator current vector are known as the *direct-axis* and *quadrature-axis* components. The direct-axis current controls the motor flux and is usually controlled to be zero with permanent-magnet machines. The motor torque may then be controlled directly by regulation of the quadrature axis component. Fast, accurate torque control is essential for high-performance drives in order to ensure rapid acceleration and deceleration—and smooth rotation down to zero speed under all load conditions.

The actual direct and quadrature current components are obtained by first measuring the motor phase currents with suitable current-sensing transducers and converting them to digital, using an on-chip ADC system. It is usually sufficient to simultaneously sample just two of the motor line currents: since the sum of the three currents is zero, the third current can, when necessary, be deduced from simultaneous measurements of the other two currents.

The controller software makes use of mathematical vector transformations, known as Park Transformations, that ensure that the three-phase set of currents applied to the motor is synchronized to the actual rotation of the motor shaft, under all operating conditions. This synchronism ensures that the motor always produces the optimal torque per ampere, i.e., operates at optimal efficiency. The vector rotations require real-time calculation of the sine and cosine of the measured rotor angle, plus a number of multiply-and-accumulate operations. The overall control-loop bandwidth depends on the speed of implementation of the closed-loop control calculations—and the resulting computation of new duty-cycle values. The inherent fast computational capability of the 26-MIPS, 16-bit fixed-point DSP core makes it the ideal computational engine for these embedded motor-control applications.

### ANALOG-TO-DIGITAL CONVERSION REQUIREMENTS

For control of high-performance ac servo-drives, fast, high-accuracy, simultaneous-sampling A/D conversion of the measured current values is required. Servo drives have a *rated operation* range—a certain power level that they can sustain continuously, with an acceptable temperature rise in the motor and power converter. Servo drives also have a *peak* rating—the ability to handle a current far in excess of the rated current for short periods of time. It is possible, for example, to apply up to six times the rated

current for short bursts of time. This allows a large torque to be applied transiently, to accelerate or decelerate the drive very quickly, then to revert to the continuous range for normal operation. This also means that in the normal operating mode of the drive, only a small percentage of the total input range is being used.

At the other end of the scale, in order to achieve the smooth and accurate rotations desired in these machines, it is wise to compensate for small offsets and nonlinearities. In any current-sensor electronics, the analog signal processing is often subject to gain and offset errors. Gain mismatches, for example, can exist between the current-measuring systems for different windings. These effects combine to produce undesirable oscillations in the torque. To meet both of these conflicting resolution requirements, modern servo drives use 12-to-14-bit A/D converters, depending on the cost/performance trade-off required by the application.

The bandwidth of the system is essentially limited by the amount of time it takes to input information and then perform the calculations. A/D converters that take many microseconds to convert can produce intolerable delays in the system. A delay in a closed-loop system will degrade the achievable bandwidth of the system, and bandwidth is one of the most important figures of merit in these high-performance drives. Therefore, fast analog-to-digital conversion is a necessity for these applications.

A third important characteristic of the A/D converter used in these applications is *timing*. In addition to high resolution and fast conversion, simultaneous sampling is needed. In any three-phase motor, it's necessary to measure the currents in the three windings of the motor at *exactly the same time* in order to get an instantaneous "snapshot" of the torque in the machine. Any time skew (time delay between the measurements of the different currents) is an

error factor that's artificially inserted by the means of measurement. Such a non-ideality translates directly into a ripple of the torque—a very undesirable characteristic.

The ADC system that is integrated into the ADMC401 provides a fast (6-MSPS), high-resolution (12-bit) ADC core integrated with dual sample-and-hold amplifiers so that two input signals may be sampled simultaneously. (As noted earlier, this allows the simultaneous value of the third current to be calculated.) The ADC core is a high-speed pipeline flash architecture. A total of eight analog input channels may be converted, accepting additional system or feedback signals for use as part of the control algorithm. This level of integrated performance represents the state-of-the-art in embedded DSP motor controllers for high-performance applications.

### POSITION SENSING AND ENCODER INTERFACE UNITS

Usually the motor position is measured through the use of an encoder mounted on the rotor shaft. The incremental encoder produces a pair of quadrature outputs (A and B), each with a large number of pulses per revolution of the motor shaft. For a typical encoder with 1024 lines, both signals produce 1024 pulses per revolution. Using a dedicated quadrature counter, it is possible to count both the rising and falling edges of both the A and B signals so that one revolution of the rotor shaft may be divided into 4096 different values. In other words, a 1024-line encoder allows the measurement of rotor position to 12-bit resolution. The direction of rotation may also be inferred from the relative phasing of quadrature signals A and B.

It is usual to have a dedicated encoder interface unit (EIU) on the motor controller; it manages the conversion of the dual quadrature

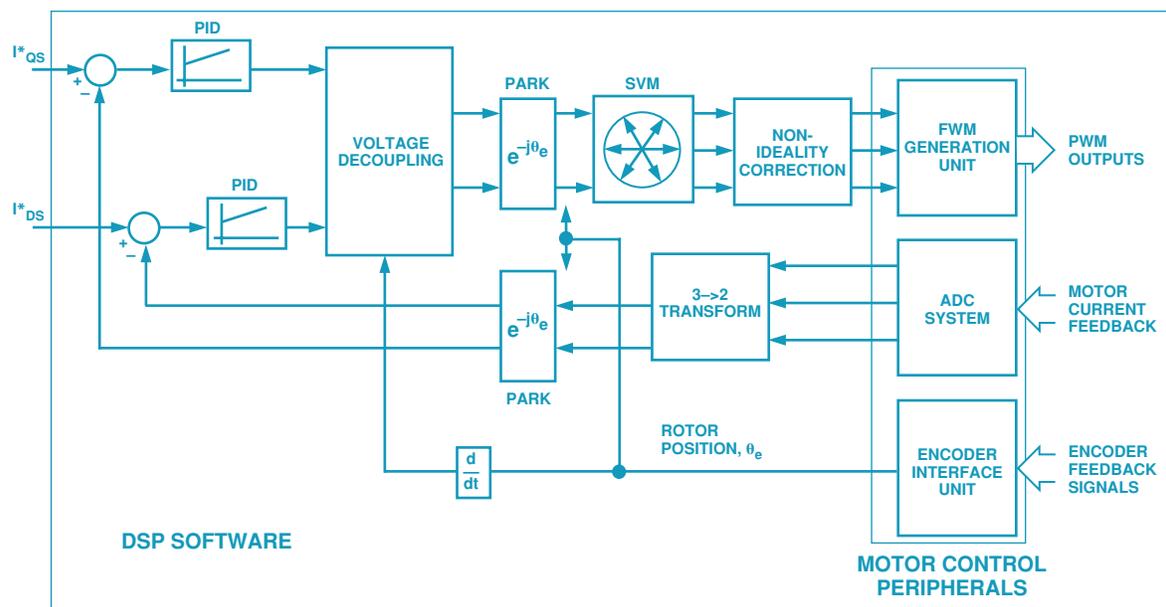


Figure 3. Configuration of typical control system for three-phase ac motor.

encoder output signals to produce a parallel digital word that represents the actual rotor position at all times. In this way, the DSP control software can simply read the actual rotor position whenever it is needed by the algorithm.

This is all very well, but there is an increasing class of cost-sensitive servo-motor drive applications with lower performance demands that can afford neither the cost nor the space requirements of the rotor position transducer. In these cases, the same motor control algorithms can be implemented with estimated rather than measured rotor position.

The DSP core is quite capable of computing rotor position using sophisticated rotor-position estimation algorithms, such as extended Kalman estimators that extract estimates of the rotor position from measurements of the motor voltages and currents. These estimators rely on the real-time computation of a sufficiently accurate model of the motor in the DSP. In general, these sensorless algorithms can be made to work as well as the sensor-based algorithms at medium-to-high speeds of rotation. But as the speed of the motor decreases, the extraction of reliable speed-dependent information from voltage and current measurements becomes more difficult. In general, sensorless motor control is applicable

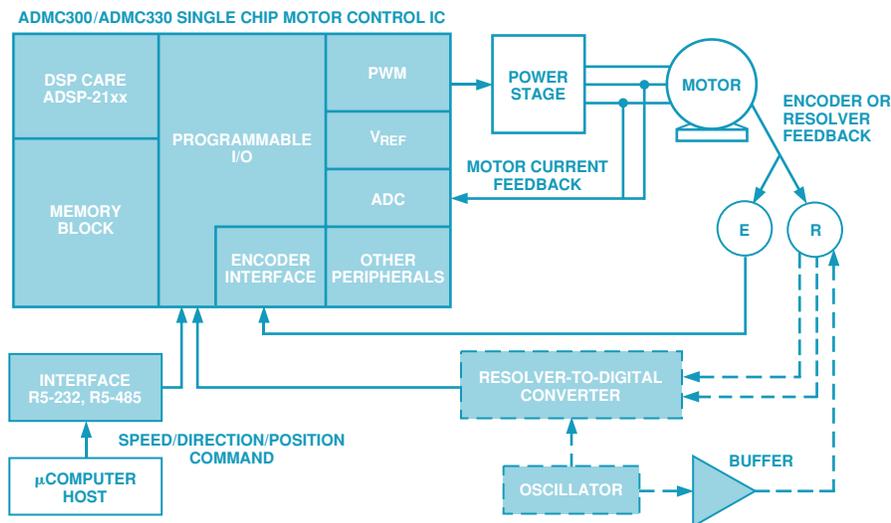
principally to applications such as compressors, fans, and pumps, where continuous operation at zero or low speeds is not required.

### Conclusions

Modern DSP-based control of three-phase ac motors continues to flourish in the market place, both in established industrial automation markets and in newer emerging markets in the home appliance, office automation and automotive markets. Efficient and cost-effective control of these machines requires an appropriate balance between hardware and software, so that time-critical tasks such as the generation of PWM signals or the real-time interface to rotor position transducers are managed by dedicated hardware units. On the other hand, the overall control algorithm and computation of new voltage commands for the motor are best handled in software using the fast computational capability of a DSP core. Implementing the control solution in software brings all the advantages of easy upgrading, repeatability, and maintainability, when compared with older hardware solutions. All motor-control solutions also require the integration of a suitable A/D conversion system for fast and accurate measurement of the feedback information from the motor. The resolution, conversion speed, and input sampling structure of the ADC system need to be strictly targeted to the requirements of specific applications.



## Mixed-Signal Motor Control Signal Chain



Using Mixed-Signal Motor Control ICs