Motor control for Military & Aerospace, Industrial and Commercial

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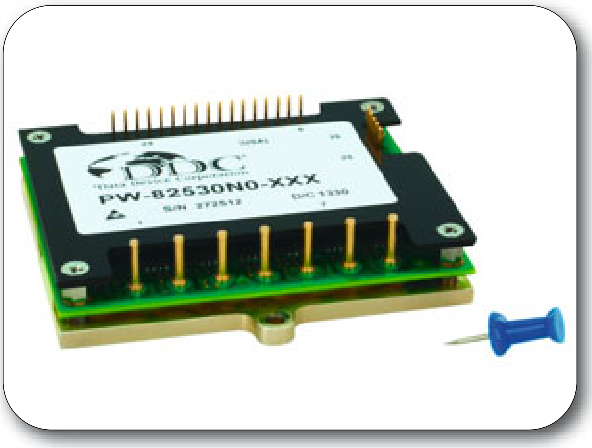
This article provides a comprehensive overview of motor drive and control technology and applications in military, aerospace, industrial and commercial fields.



■ In addition to multiple environmental requirements, different motor controllers and drive applications have varying functional and performance requirements, such as: highly accurate speed and position control. Position controllers typically require the controller to track a velocity profile of acceleration, constant speed, deceleration, and precise positioning. One example requiring highly precise speed and position control is industrial CNC machines. Constant and/or variable speed: for example, while a reaction of a spacecraft wheel will not experience rapid load changes, its motor drive must provide good speed accuracy to maintain attitude control. Such accuracy requires a torque controller with an additional speed control loop. Rapid reversal is a common requirement in many industrial applications. Constant speed or position, but with varying loads: an example of a drive requiring constant speed is a hydraulic pump that needs to provide a constant flow rate, while needing to compensate for rapid load variations. This demands that the bandwidth of the velocity control loop exceed the rate of load change. Similarly, flight actuators must maintain a fixed position while reacting to rapidly changing load conditions.

For the various applications mentioned, different types of motors are used. AC induction or asynchronous motors are commonly used in industrial motion control applications and home appliances. Since three-phase and single-phase induction motors are rugged, reliable and economical, they are widely used in industrial drives and smaller loads for household appliances like fans where precise speed or positioning control is not required. In an induction motor, the electric current in the rotor needed to produce torque is induced by electromagnetic induction from the magnetic field of the stator winding. Unlike a DC motor, an induction motor does not require mechanical or electronic commutation. Brushed DC motors are used in applications including electrical propulsion, cranes, paper machines, and steel rolling mills. Brushed DC motors run from simple drives not requiring electronic commutation, and may be controlled by means of the armature voltage or field current. Motor speed may be increased with increasing armature voltage. Alternatively, at low to medium levels of torque load, motor speed may be increased by reducing field current.

All motors require a varying electric field in order to operate. To operate from a DC voltage source, brushed motors are self-commutating, meaning changes in current direction (commutation) are handled by the motor itself. The commutation of a brushed motor is performed mechanically by means of brushes that apply DC current to the rotating armature. Advantages of brushed DC motors include: high power levels, high efficiency, low cost, simple to control, good operation in rough environments. Disadvantages of brushed DC motors include: require periodic maintenance to replace brushes, at high speeds brush friction increases reducing torque output, high rotor inertia, and electromagnetic interference (EMI) resulting from brush arcing.

Brushless DC (BLDC) motors are often preferred over brushed DC motors. BLDC motors use rotating permanent magnets and stator windings. In lieu of brushes, BLDC motors must be electronically commutated. Commutation logic controls the switching of the drive electronics, enabling current phases of the motor windings to vary in a precise sequence. Brushless DC motors are synchronous motors powered by a DC electric source developed from a switching power supply. BLDC motors typically include three phase windings, with each winding powered by a separate circuit. Phase currents are commutated or reversed based on rotor position, which is sensed by means of a rotary encoder or Hall effect sensors. Brushless DC motors include a number of advantages, in particular relative to brushed DC motors: higher torque per weight, higher torque per watt (higher efficiency), increased speed range, increased reliability (no brushes to replace), elimination of the rotor windings found

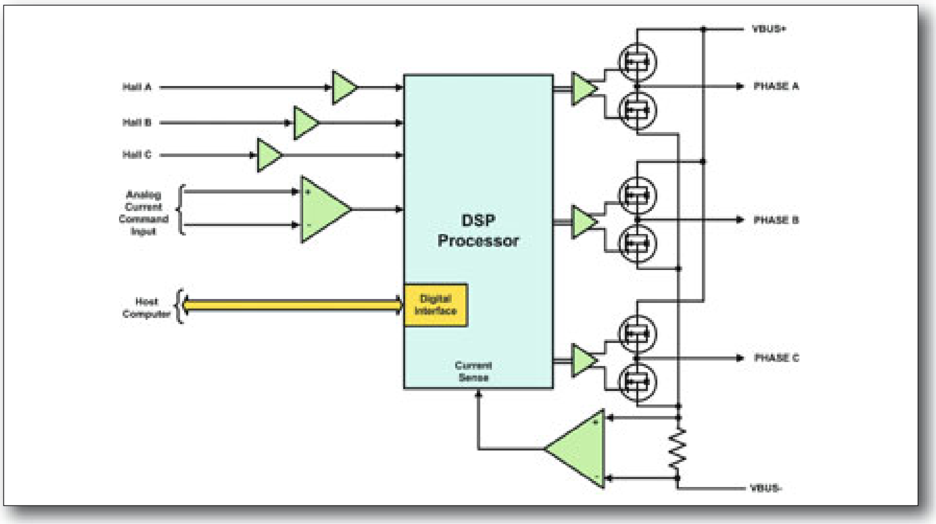


Figure 1. 3-phase brushless DC motor drive block diagram

in brushed motors reduces inertia. Since the motor windings are supported by its housing, brushless DC motors can be conduction-cooled, eliminating the need for airflow. This also allows the motor to be fully enclosed and protected for use in dirty environments. It also eliminates EMI and ionizing sparks from commutating brushes.

Considerations for DC motor drive and controller selection include voltage, current, and horsepower requirements; position, speed, and current accuracy; dynamic response; power dissipation and efficiency; and the physical form factor and size of the drive. Figure 1 shows the block diagram of a representative 3-phase BLDC motor drive. Such a drive provides closed loop current control, with the set point input provided either as a differential DC analog signal or by means of the digital interface of the controller, which could be USB, serial, CANbus, or Ethernet. To enable electronic commutation, motor shaft position feedback is provided by means of three Hall effect sensors. Closed loop current control and motor commutation is implemented by software running on the drive's DSP microprocessor. Figure 2(a) shows a representation of a 3-phase BLDC motor, while figure 2(b) shows the motor current and torque waveforms.

Many motor drives provide complementary 4-quadrant operation. A 4-quadrant drive is capable of either driving or providing braking (regeneration) to a motor in either direction. To provide bidirectional torque and current control, 3-phase, 4-quadrant drives include high and low-side MOSFETs for each phase, as shown in figure 1. In addition to providing 4-quadrant operation, these drives enable a seamless transition through zero amps by driving the motor with a 50% duty cycle waveform at the PWM frequency of the drive. This enables linear current control through zero amps with no deadband.

To provide clockwise torque, the PWM positive duty cycle increases above 50%. To provide counterclockwise torque, the PWM duty cycle decreases below 50%. In either case, the drive provides a net positive or negative average DC current with motor torque directly proportional to the average current value. Motor commutation is controlled by inputs from three Hall effect sensors mounted on the motor shaft. Figure 2(b) shows an example of three-phase motor commutation. At any point in time, one phase is driven positive (to VBUS+), one phase is driven negative (to VBUS-), while the third phase is not driven. In the example of figure 1, a single current-sensing resistor and differential amplifier is used to provide motor current feedback. To filter out the effects of ripple current, current sampling and digitizing is performed multiple times for each control loop cycle. In some drives, multiple current-sensing circuits are used in order to monitor two phases or all three phases. By using full-on and full-off switching, pulse width modulation (PWM) provides high power efficiency, minimizing the internal power dissipation of the motor drive. Typical PWM frequencies are in the range of 10 to 100 kHz. High-frequency PWM increases controller bandwidth and minimizes current and torque ripple.

Some motor drives allow user selection of PWM frequency. Since switching power dissipation increases proportionally to frequency, there is an inherent tradeoff of drive bandwidth and reduced current and torque ripple, provided by increasing the PWM frequency, and drive power dissipation, which is lowered by reducing the PWM frequency. Motors with relatively low inductance require higher PWM frequencies to limit the amount of current

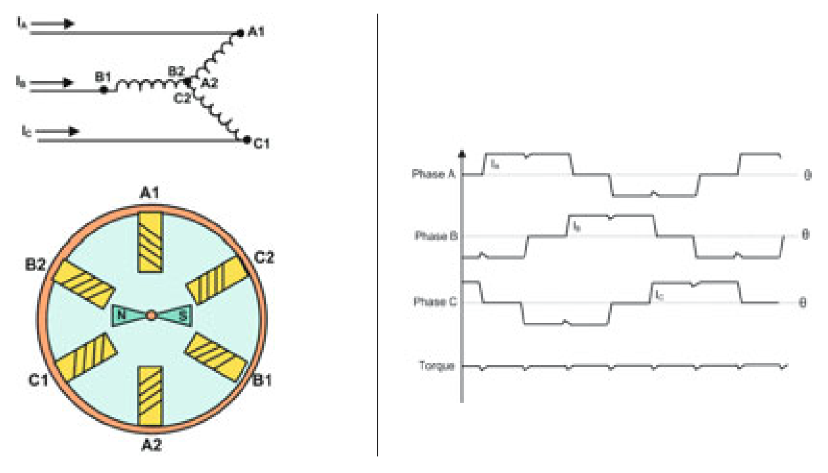


Figure 2. Brushless DC motor: (a) motor representation; (b) 3-phase current envelope and torque waveforms.

Figure 3. Hybrid motor drive and controller solutions: (a) DDC PWR-82340 200V/500V, 30A H-bridge drive; (b) PWR-82333 500V, 30A 3-phase drive; and (c) PW-82540R0 radiation-tolerant 3-phase DC motor torque controller.

and torque ripple. PWM frequency may be optimized for different applications depending on motor inductance, control loop bandwidth requirements, and the tolerable level of drive dissipation. The drive control processor provides high bandwidth control by varying the PWM duty cycle. Accurate and rapid control of current and therefore motor torque is an essential building block for implementing high performance velocity and position control systems. In addition, control of motor current enables fast reaction to short-circuit fault conditions by rapidly reducing the PWM duty cycle following detection of large increases in motor current.

The most common type of control loop for controlling motor current, speed, and position is the PID, or proportional-integral-derivative loop. In some cases, PI or proportional-integral, rather than full PID control is used. This is because some feedback signals include relatively large AC and/or noise components, making it impractical to include their time derivative into the motor control algorithm. For controlling motor current, the analog form of the PI control loop equation is: Where e(t) = current error = ISETPOINT - IOUT, KP = proportional gain, and KI = integral gain, W = the input to the motor drive pulse width modulator (PWM). The inclusion of the 0.5 offset will result in the desired PWM duty cycle of 50% when ISETPOINT = IOUT = 0.

With a processor-based motor controller, PI control is implemented as a digital control loop, as follows:

Proportional term: ; Integral term: if e(k) ≤ eMAX, then , and if e(k) > eMAX, then . (see below); Composite "P + I" input to PWM controller: .

There are multiple ways for tuning the values of KP and KI in order to optimize current control loop operation. The optimal tuned values of KP and KI will vary as a function of motor resistance, inductance and torque constant, control loop sampling rate, PWM frequency, and motor load parameters. The advantages of PI control include the following. The PI and PID algorithms are extremely mature, relatively simple, and well understood by the industry. As a result, their use greatly facilitates system integration by end users. PI control loops are flexible, and minimize the level of understanding of motor and load characteristics required to configure stable, high performance systems. The KP and KI coefficients are typically tuned to optimize controller response. Depending on system requirements, the response to a step change in current setpoint may be tuned to either minimize overall settling time, or to eliminate or minimize overshoot. The integration term WI(k) eliminates steady state errors to step inputs in the current setpoint. Eliminating the WI(k) integration term when e(k) is large (> ±eMAX) prevents integrator "windup". Without this rule, WI(k) could saturate the controller output following a large change in the current setpoint, with the result being an increase in the controller settling time or continuous oscillation. The simplicity and familiarity of PI control loops allows PI torque (current) controllers to be readily nested into additional "outer" PI or PID loops controlling motor velocity and position.

For military, aerospace and industrial applications, there are many types of solutions available. These can take the form of highly rugged and compact hybrids, modules, or card assemblies. An example is the new PW-82530 from Data Device Corporation (DDC). This is a fully self-contained 3-phase, closed loop current/torque controller capable of driving 10 amps of output current with bus voltages up to 100 volts. The PW-82530 provides processor-based current control including user-tunable PI parameters with menu software, and Hall effect sensor-based commutation. The current setpoint input may be provided through either a differential analog input or through the USB interface of the module. Additional features include complementary 4-quadrant operation including regenerative braking, cycle-by-cycle current limit, a PWM frequency from 10 to 100 kHz, and PC board mounting with a thermal interface enabling conduction cooling.

For applications requiring very small size and light weight, hybrid microcircuit solutions (figure 3) are an excellent choice. All these solutions provide 4-quadrant operation from -55°C to +125°C. For example, the PWR-82340 is a 200V or 500V, 30A high-efficiency H-bridge drive for driving single-phase brushed or brushless DC motors using a MOSFET or IGBT drive stage, and operating from a PWM input. Similarly, the PWR-82333 is a 500V, 30A 3-phase drive providing a six-step direct drive from commutation logic and featuring a very low JC of 0.85°C/W. For space applications requiring radiation tolerance and high reliability, the PW-82332 is a 3-phase, 400 volt, 19 amp, MOSFET motor drive providing total dose immunity of 10 Krads, a LET threshold of 36 MeV/mg/cm2, direct drive from commutation logic, and switching frequencies up to 50 kHz. The PW-82332 has been qualified for space station use and is available with Class K screening. ■