White Paper

MOTION CONTROL

BLDC Motor Control in Demanding Environments

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BLDC Motor Control in Demanding Environments

Introduction

Motor drives and controllers are used in a variety of applications spanning a number of different environments. Military applications include antennas and sensor positioning, stabilized platforms, guns and cannons and turret control, ship steering/rotor control, bomb and missile fins, pumps, and simulation systems. Military and commercial aviation applications include actuators, landing gear, and emergency power units. For civil aircraft, the ongoing transition away from mechanical and hydraulic and towards “more electric” systems has increased the demand for high reliability electronic motor controllers.

Space applications include reaction wheels, positioning for solar arrays, space robotics, and antenna/camera/telescope positioning. Industrial applications include wafer processing, wire bonding machines, robotics, printing equipment, textile machines, CNC machines, plasma cutting machines, and injection molding. Additional commercial applications include automotive, with power steering, transmission actuation, and engine cooling; and home appliances, including clothes washers and dryers, room air conditioners, refrigerators and freezers, and vacuum cleaners.

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 spacecraft’s reaction 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.

Types of Motors

For the various applications mentioned above, different types of motors are used.

AC induction or asynchronous motors

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

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, brush 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
- Operate well 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
- Electromagnetic interference (EMI) resulting from brush arcing

Brushless DC (BLDC) motors

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. 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)
- Eliminating the rotor windings found in brushed motors reduces inertia
- Since the motor's 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.
- Elimination of EMI and ionizing sparks from commutating brushes

Motor Drives

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 setpoint input provided either as a differential DC analog signal or by means of the controller's digital interface, 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's 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 drive's PWM frequency. This enables linear current control through zero amps with no deadband.

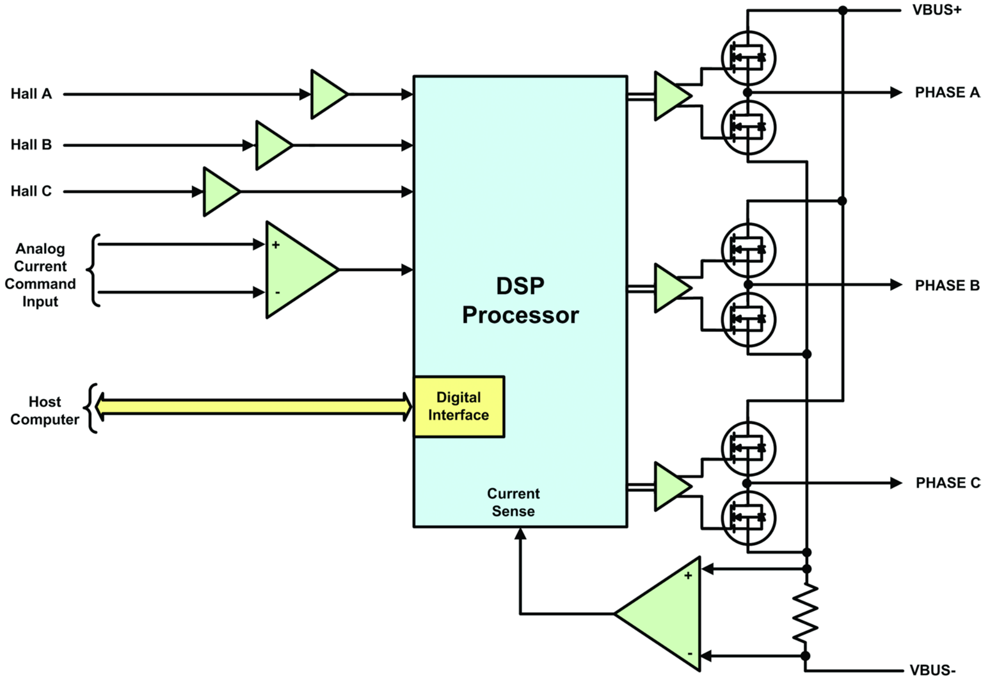


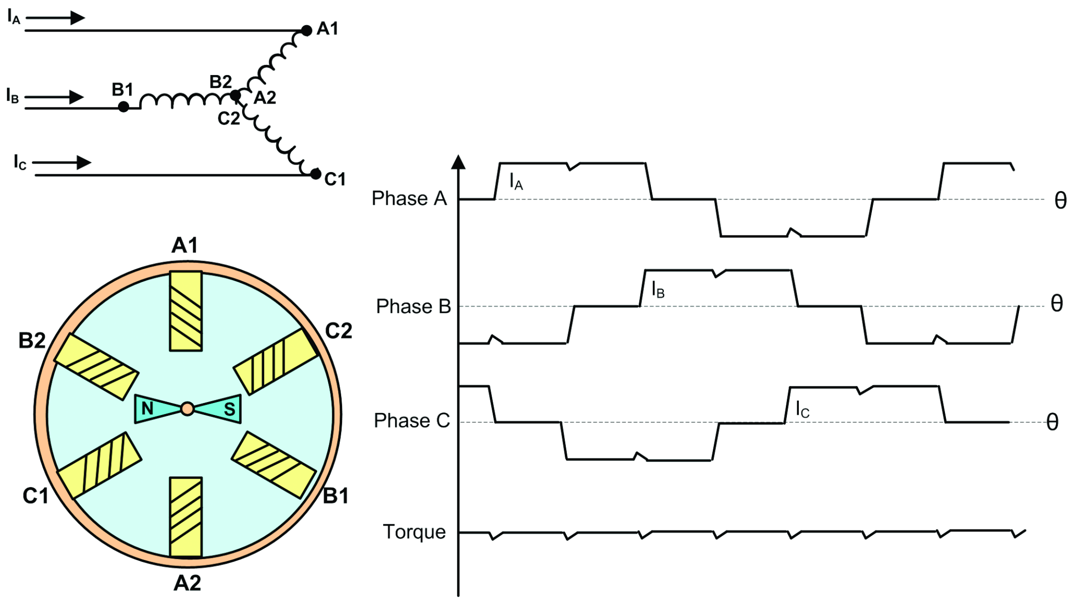
Figure 1. 3-Phase Brushless DC Motor Drive Block Diagram

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 controllers, 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 motor drive's internal power dissipation. Typical PWM frequencies are in the range of 10 to 100 KHz. High-frequency PWM increases controller bandwidth and minimizes current and torque ripple.



(a) **(b)**

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

Some motor drives allow user selection of PWM frequency. Since switching power dissipation increases proportionally to frequency, there's an inherent tradeoff of drive bandwidth and reduced current and torque ripple, provided by increasing the PWM frequency; and drive switching 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 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's 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.

Digital Control Loop

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:

$$W = 0.5 + \left(K_P \bullet e(t) + \left(K_I \bullet \int_0^t e(t)dt\right)\right),$$

where:

- $e^{(t)}$ = current error = $I_{SETPOINT} - I_{OUT}$
- K_P = proportional gain
- K_I = integral gain
- W = the input to the motor drive's pulse width modulator (PWM). The inclusion of the 0.5 offset will result in the desired PWM duty cycle of 50% when $I_{SETPOINT} = I_{OUT} = 0$.

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

- Proportional term: $W_P(k) = K_P \bullet e(k)$
- Integral term:
  - if $|e(k)| \leq e_{MAX}$, then $W_I(k) = W_I(k-1) + \left(K_I \bullet e(k)\right)$
  - if $|e(k)| > e_{MAX}$, then $W_I(k) = 0$ (see below)
- Composite "P + I" input to PWM controller: $W(k) = 0.5 + K_P(k) + K_I(k)$

There are multiple ways for tuning the values of K_P and K_I in order to optimize current control loop operation. The optimal tuned values of K_P and K_I 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 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 K_P and K_I 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 $W_I(k)$ eliminates steady state errors to step inputs in the current setpoint.
- Eliminating the $W_I(k)$ integration term when e(k) is large ($> \pm e_{MAX}$) prevents integrator "windup". Without this rule, $W_I(k)$ 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 for controlling motor velocity and position.

Motor Control Solutions

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.

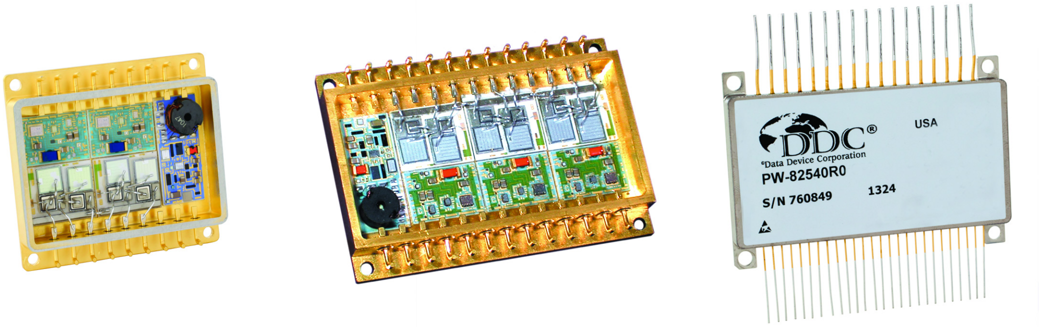
An example, shown in Figure 3, is the PW-82560 from Data Device Corporation (DDC). The is a fully-self-contained 3-phase, programmable closed loop current/torque or voltage/speed controller capable of driving 30 amps of output current with bus voltages up to 100 volts. This device has an included Graphical User Interface (GUI) for device programming that will enable the user to optimize performance in their system. The PW-82560 provides processor-based motor control including user-tunable PI parameters and programmable Hall Effect sensor or sensorless commutation. The speed or current command input may be provided through either a differential analog serial bus (USB, RS422 or RS485). Additional features include complementary 4-quadrant operation, cycle-by-cycle current limit, acceleration/deceleration, soft start, PWM frequency from 10 to 50 KHz, and PC board mounting with a thermal interface enabling conduction cooling.

Figure 3. DDC PW-82560 3-Phase Motor Controller

For applications requiring very small size and light weight, hybrid microcircuit solutions (Figure 4) are an excellent choice. All of these solutions provide 4-quadrant operation from -55˚C to +125˚C. For example, the PWR-82340 (Figure 4a) 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 (Figure 4b) is a 500V, 30A 3-phase drive providing a six-step direct drive from commutation logic and featuring a very low θ_{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, an LET threshold of 36 MeV/mg/cm^2, 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. The PW-82540R0 (Figure 4c) is a 100V, 10-Amp radiation-tolerant torque controller providing a total dose immunity of 100 krads.



(a) **(b)** **(c)**

Figure 4. 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

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Data Device Corporation (DDC) is the world leader in the design and manufacture of high-reliability data bus, motion control, and solid-state power controller products for aerospace, defense, and industrial applications. For 50 years, DDC has continuously advanced the state of high-reliability data communications and control technology for Motor Control, MIL-STD-1553, ARINC 429, AFDX®, Synchro/Resolver interface, and Solid-State Power Controllers with innovations that have minimized component size and weight while increasing performance. DDC headquarters, design and manufacturing operations are located in Bohemia, NY. Visit www.ddc-web.com .

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Data Device Corporation (DDC) is the world leader in the design and manufacture of high-reliability data bus products, motion control, and solid-state power controllers for aerospace, defense, and industrial automation applications. For more than 50 years, DDC has continuously advanced the state of high-reliability data communications and control technology for MIL-STD-1553, ARINC 429, Synchro/Resolver interface, and Solid-State Power Controllers with innovations that have minimized component size and weight while increasing performance. DDC offers a broad product line consisting of advanced data bus technology for Fibre Channel networks; MIL-STD-1553 and ARINC 429 Data Networking cards, components, and software; Synchro/Resolver interface components; and Solid-State Power Controllers and Motor Drives.

Product Families

Data Bus | Synchro/Resolver | Power Controllers | Motor Drives

DDC is a leader in the development, design, and manufacture of highly reliable and innovative military data bus solutions. DDC's Data Networking Solutions include MIL-STD-1553, ARINC 429, and Fibre Channel. Each Interface is supported by a complete line of quality MIL-STD-1553 and ARINC 429 commercial, military, and COTS grade cards and components, as well as software that maintain compatibility between product generations. The Data Bus product line has been field proven for the military, commercial and aerospace markets.

DDC is also a global leader in Synchro/Resolver Solutions. We offer a broad line of Synchro/Resolver instrument-grade cards, including angle position indicators and simulators. Our Synchro/Resolver-to-Digital and Digital-to-Synchro/Resolver microelectronic components are the smallest, most accurate converters, and also serve as the building block for our card-level products. All of our Synchro/Resolver line is supported by software, designed to meet today's COTS/MOTS needs. The Synchro/Resolver line has been field proven for military and industrial applications, including radar, IR, and navigation systems, fire control, flight instrumentation/simulators, motor/motion feedback controls and drivers, and robotic systems.

As the world's largest supplier of Solid-State Power Controllers (SSPCs) and Remote Power Controllers (RPCs), DDC was the first to offer commercial and fully-qualified MIL-PRF-38534 and Class K Space-level screening for these products. DDC's complete line of SSPC and RPC boards and components support real-time digital status reporting and computer control, and are equipped with instant trip, and true I^2T wire protection. The SSPC and RPC product line has been field proven for military markets, and are used in the Bradley fighting vehicles and M1A2 tank.

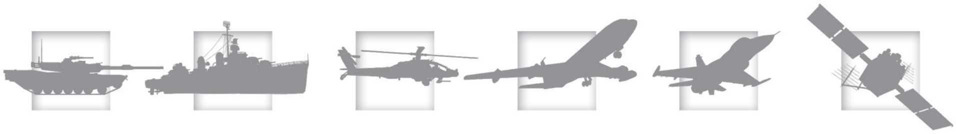
DDC is the premier manufacturer of hybrid motor drives and controllers for brush, 3-phase brushless, and induction motors operating from 28 Vdc to 270 Vdc requiring up to 18 kilowatts of power. Applications range from aircraft actuators for primary and secondary flight controls, jet or rocket engine thrust vector control, missile flight controls, to pumps, fans, solar arrays and momentum wheel control for space and satellite systems.

Certifications

Data Device Corporation is ISO 9001: 2008 and AS 9100, Rev. C certified.

DDC has also been granted certification by the Defense Supply Center Columbus (DSCC) for manufacturing Class D, G, H, and K hybrid products in accordance with MIL-PRF-38534, as well as ESA and NASA approved.

Industry documents used to support DDC's certifications and Quality system are: AS9001 OEM Certification, MIL-STD-883, ANSI/NCSL Z540-1, IPC-A-610, MIL-STD-202, JESD-22, and J-STD-020.



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