



Drive And Control Electronics Enhance The Brushless Motor's Advantages

With the appropriate driver IC and microcontroller, designers can exploit the brushless motor's declining price, smaller size, lighter weight, and minimal maintenance.

As recently as two years ago, brushless motors were significantly more expensive than brush motors. However, advances in design and materials have triggered dramatic price drops in brushless motors. Today, the cost differential between these two motor technologies is only about 10%.

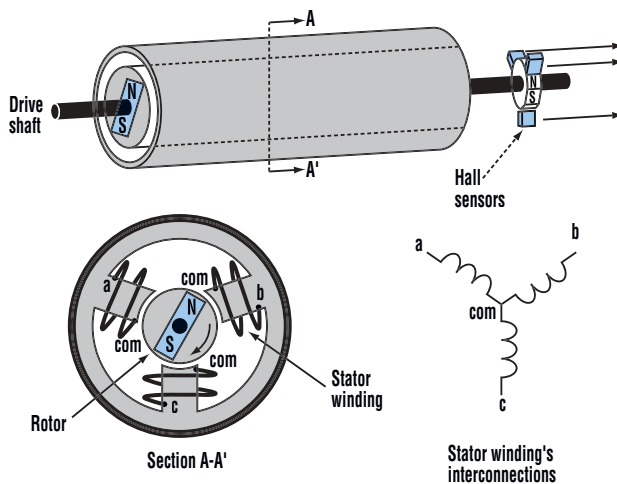
Brushless motors with the same horsepower as brush motors are smaller and lighter. Because they lack this brush-commutator interface, brushless motors exhibit lower acoustic noise. They're also virtually maintenance free. And, they exhibit a longer life.

Eliminating the brush-commutator interface requires control and driver electronics that deliver power to the brushless motor. Plus, the availability of microcontrollers that contain motion-control algorithms enable brushless motors to provide the desired performance. But to understand the electronics employed to drive a brushless motor, we should first review the electromechanical commutation of a brush motor.

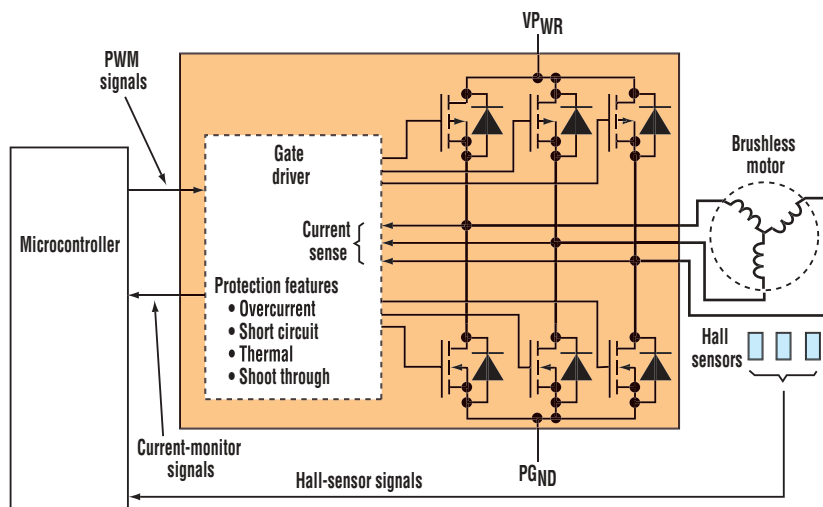
Brushes apply a sequence of voltages to the proper motor windings. In operation, graphite brushes contact a circular, multiple-segment commutator on the motor shaft, providing the voltage switching action at the proper times. This switching action maximizes torque as the motor shaft rotates throughout each full 360° rotation.

Yet in a brushless motor, switching electronics that use Hall-effect sensors usually perform the commutation (Figures 1 and 2). These sensors send the drive electronics to the electrical position of the rotor every instant.

Most brushless-motor manufacturers supply motors with three Hall-effect position sensors, each delivering an alternating binary high and low as the rotor turns. The three sensors are offset so each aligns with one of the fields developed by one of the wound stator poles (Fig. 1, again). Two windings are always energized while one winding is not (Fig. 3).



1. A brushless dc motor employs Hall sensors rather than the familiar brush-commutator configuration of a conventional dc motor with brushes.



2. A microcontroller and Apex's SA305 brushless-motor driver IC provide the necessary functions to drive a brushless motor.

PWM DRIVE • Traditionally, brushless motors are driven with a linear amplifier (Fig. 4a). A linear control circuit exhibits a worst case efficiency of 50% when driving resistive loads at midrange power levels.

Today, most of these motors use pulse-width modulation (PWM), which converts an analog-input voltage into a variable-duty-cycle drive signal (Fig. 4b). Beginning at zero duty cycle (OFF all the time), the duty cycle advances as the motor begins to rotate, until it's running at the speed and/or torque required by the application.

Losses in a PWM control circuit are primarily due to the on resistance of the switching MOSFET and the flyback diode, which means that efficiencies are as high as 80% to 95%. At high switching frequencies, though, the energy required to turn the MOSFETs on and off can become significant.

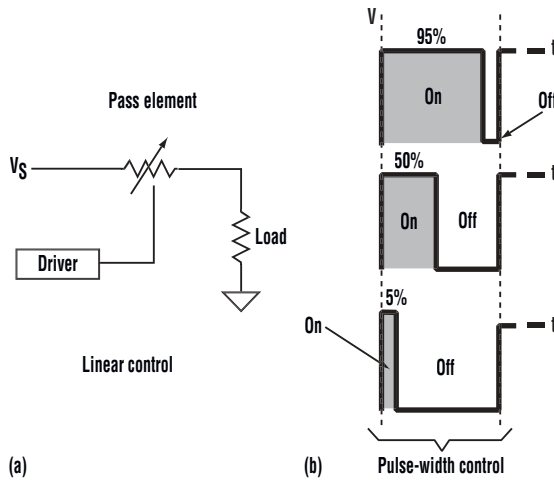
Besides enhanced efficiency, PWM also can limit startup current, controlling speed and torque. The optimum switching frequency depends on inertia, the brushless motor's inductance, and the application.

Generally, raising the switching frequency increases the PWM losses. On the other hand, lowering the switching frequency limits the system's bandwidth and can raise the ripple current pulses to the point where they become destructive or shut down the brushless motor driver.

Until the introduction of brushless-motor driver ICs, designers of three-phase brushless motors had to configure three discrete gate drivers and six MOSFETs. One example of an integrated, fully protected, three-phase, brushless motor driver IC available today is the SA305.

Developed by Apex Microtechnology, this IC can deliver up to 300 W using DMOS power output devices and CMOS control logic². It includes overcurrent, short-circuit, and thermal protection. Also, it will shut down if the instantaneous current exceeds 12 A.

The IC in the three-phase brushless-motor application has three independent, DMOS FET half bridges that pro-



4. Illustrated are two motor-control techniques: a traditional linear control technique (a), and one that employs PWM control, which exhibits far lower losses than the linear drive approach (b).

vide up to 10-A peak output current under microcontroller or DSP control (Fig. 2, again). In operation, as the motor rotor revolves, the controller causes one motor terminal to be driven high, a second low, and the third to float (Fig. 3, again).

Proper synchronization of this sequence is ensured by the feedback from the Hall sensors. At every instant, the sensors keep the microcontroller informed of the rotor's position with regard to the stator windings.

Shoot-through can occur if both the upper and lower portions of two half bridges are turned simultaneously. This

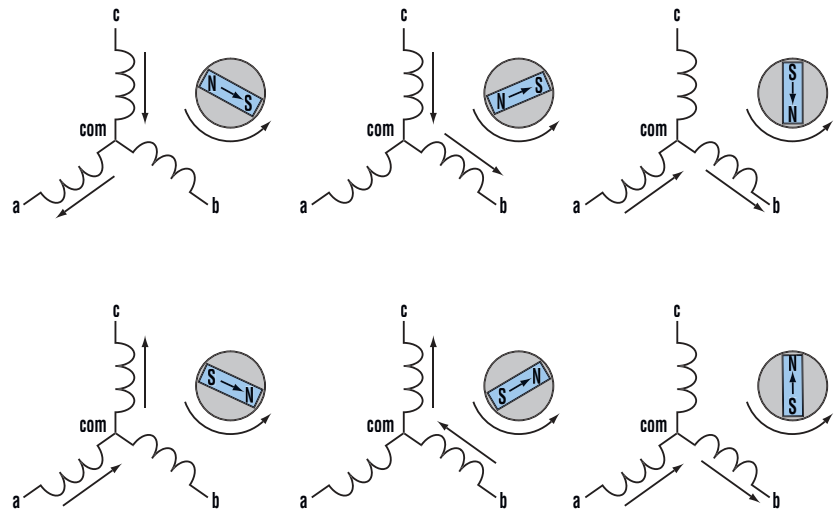
must be avoided because it would overload the circuit and destroy the MOSFETs. To prevent this, the SA305 inserts a dead time so the MOSFETs can fully commute to the next state before power is applied to the ON MOSFETs. The SA305 also provides fault status indication and can monitor the current in each of the three motor phases.

A microcontroller, or other intelligent logic, can control virtually all brushless motors. For example, Microchip's PIC18F2331 includes a 14-bit power control PWM module with programmable, dead-time insertion to prevent shoot through (Fig. 5).

Though you can turn to a number of sources for assistance when choosing a motor, brushless or otherwise, a good starting point is Reference 1. It points out how choosing a motor requires a look at efficiency, torque, power reliability, and cost.

BRUSHLESS MOTOR BEHAVIOR • One of the critical operational conditions for a brushless motor is when it is at rest and then applies power. At that time, the rotor is stationary and delivering no back electromotive field (V_{BEMF}), expressed as:

$$V_{BEMF} = (K_b)(\text{Speed}) \quad (1)$$



3. By monitoring the Hall-effect sensors, the brushless-motor stator-winding fields rotate so that the resultant field of the two energized stator windings and the pole of the permanent magnet rotor remain at right angles. This maximizes its instantaneous torque.

where K_b = voltage constant (V/1000 rpm) and speed = thousands of revolutions per minute.

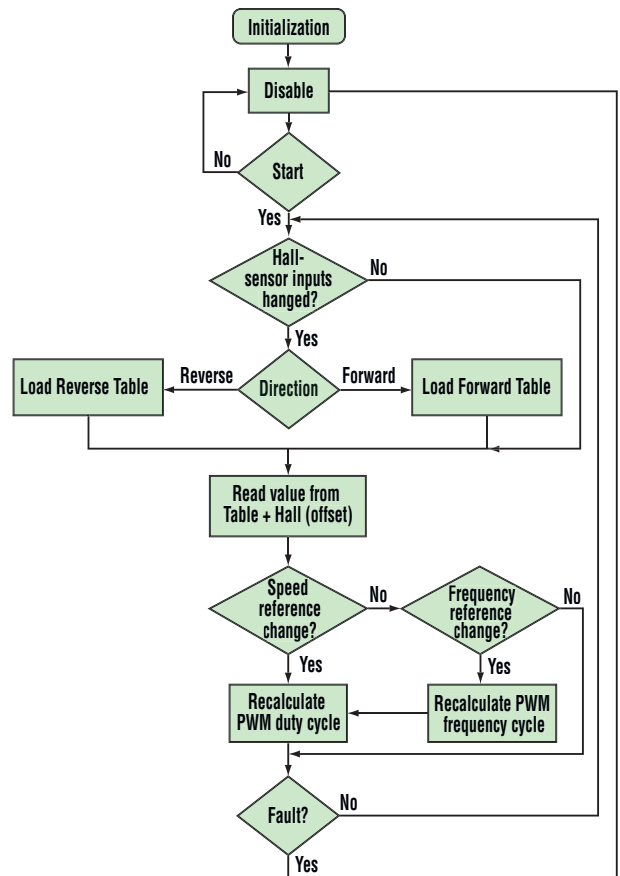
Once a voltage is applied to the motor, the rotor begins turning and generates a V_{EMF} governed by Equation 1. If we ignore for the moment that we plan to drive the motor with a PWM source and assume the motor is driven by a steady-state voltage, then the current is governed by:

$$I = [(V - V_{EMF})/R_m][1 - e^{-R_m t/L_m}] \quad (2)$$

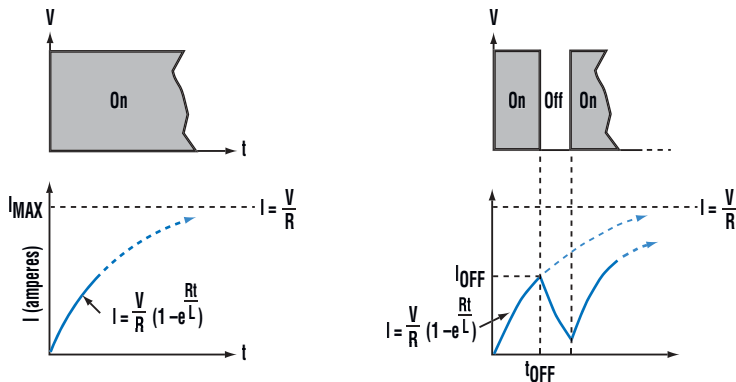
where V = applied voltage; V_{EMF} = back EMF; R_m = stator resistance (winding pair); and L_m = stator inductance (winding pair).

In Equation 2, the current (I) at any moment is a function of both the back EMF (V_{EMF}) and the time constant (L_m/R_m). Figure 6a, which shows the current when the motor is stopped ($V_{EMF} = 0$), is the familiar waveform for characterizing the current in any L-R circuit, with its rise time governed by the time constant L/R .

Now, exchange the steady-state excitation voltage for a PWM source (Fig. 6, right). The current rises until the first ON pulse ends. When the voltage abruptly falls to zero at the end of the first applied voltage pulse, the current begins to decay toward zero. However, the next pulse will again drive the current upwards, and so forth, so the current continues to rise.



5. Here is the brushless-motor microcontroller algorithm for Microchip's PIC18F2331 microcontroller.



6. Brushless motor current behavior is shown with steady-state excitation (left) and PWM excitation (right).

As the motor accelerates, the current waveform exhibits a sawtooth profile, known as ripple. Because torque is directly proportional to current, the sequence of rising current pulses drives the motor, developing a corresponding torque that accelerates the motor. Figure 6 shows the ripple current pulses.

Applied voltage, switching frequency, and the PWM duty cycle are three crucial parameters that can be programmed independently. Selecting these variables determines how fast the motor will accelerate, as well as its speed and torque.

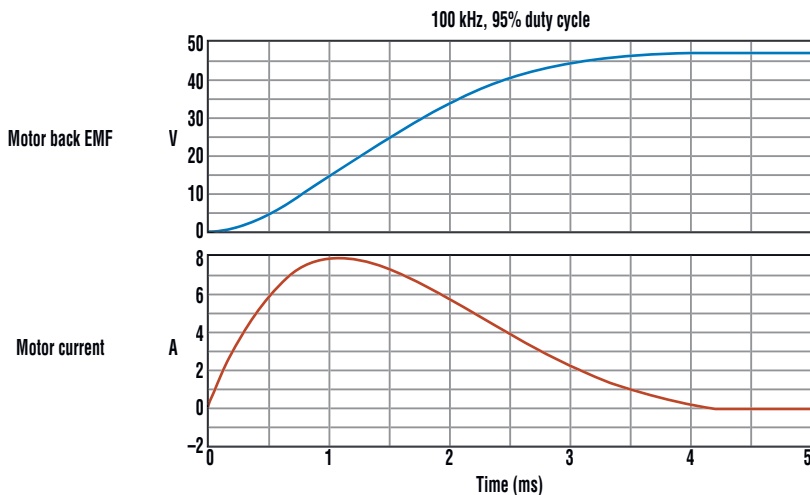
DESIGN EXAMPLE • As an example, choose a low-inertia, brushless motor that delivers 55 oz-in. of torque at 5000 rpm, such as the Galil Motion Control BLM-N23-50-1000-B. With this motor, any stator-winding pair exhibits a

resistance (R_m) of 1.2 Ω and an inductance (L_m) of 2.6 mH.

The torque constant (K_t) of the motor is 12.1 oz-in./A, and the voltage constant K_b is 8.9 V/1000 rpm. The first step is to ensure that the SA305's 12-A maximum current capability isn't exceeded, which would cause the IC and the drive circuit to shut down.

If $V/R > 12$ A regardless of the other parameters, the current can never reach this value. This can be seen in Figure 6, where both the first and all succeeding pulses approach the value of V/R . Another way of looking at it is that the current in any L-R circuit can never exceed V/R . Consequently, the applied voltage, which includes any instantaneous ripple, will never shut down the SA305.

If $V/R > 12$ A, then several factors in our design must be considered, including R_m 's value of 1.2 Ω . If we assume a 60-V



7. Dynamic simulation results are given for the Galil BLM-N23-50-1000-B brushless motor.

drive, then $V/R = 60/1.2 = 50$ A. When we apply the initial voltage to the motor, the current ramps up as explained in Equation 2. As the back EMF builds, the current tapers off (*Fig. 7*).


We may never see the maximum current in normal operation because of the back EMF. The motor's torque constant and the inertial load will govern the rate at which the motor comes up to speed. If the motor has a particularly low L/R time constant relative to the mechanical time constant, the current can reach the maximum well before the motor builds any back EMF.

Note that in this example the simulation in Figure 7 shows that current will never exceed 8 A—well below 12 A. If the current were to exceed the limit of the driver, adding external series resistance or inductance would limit the peak current and di/dt , respectively, but each would adversely affect system performance.

We can safely accelerate the motor if we control the startup current with a

PWM drive by limiting the duty cycle of each pulse so as not to exceed the maximum peak current rating of the driver. The SA305's current monitor feature makes this type of feedback relatively simple to implement.

By employing a microcontroller and monitoring the instantaneous currents in all three phases, we can develop a closed-loop algorithm for startup purposes, which would hold the peak current near 12 A without exceeding it. Actually, a small amount of headroom makes sense, so program it for 11-A motor current.

The advantage of this approach is that it optimizes the run up, keeping the current as high as possible so the acceleration is as high as possible. In such an approach, the duty cycle would be modulated based on the current sensed in the three phases (*Fig. 2, again*). References 3, 4, and 5 offer even more information about using microcontrollers to drive brushless motors. 

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