Brushless DC Motors - Part I: Construction and Operating Principles

Pushek Madaan, Cypress Semiconductor - February 11, 2013

Electrical equipment often has at least one motor used to rotate or displace an object from its initial position. There are a variety of motor types available in the market, including induction motors, servomotors, DC motors (brushed and brushless), etc. Depending upon the application requirements, a particular motor can be selected. However, a current trend is that most new designs are moving towards Brushless DC motors, popularly known as BLDC motors.

This article will concentrate on the following aspects of BLDC motor design:

- Construction of the BLDC motor
- Operation of the BLDC motor
- Torque and Efficiency requirements
- Comparison with Induction and Brushed DC motors
- Selection criteria for a BLDC motor
- Motor control - Speed, Position and Torque, to be covered in Part II of this article.

Construction

BLDC motors have many similarities to AC induction motors and brushed DC motors in terms of construction and working principles respectively. Like all other motors, BLDC motors also have a rotor and a stator.

Stator

Similar to an Induction AC motor, the BLDC motor stator is made out of laminated steel stacked up to carry the windings. Windings in a stator can be arranged in two patterns; i.e. a star pattern (Y) or delta pattern (Δ). The major difference between the two patterns is that the Y pattern gives high torque at low RPM and the Δ pattern gives low torque at low RPM. This is because in the Δ configuration, half of the voltage is applied across the winding that is not driven, thus increasing losses and, in turn, efficiency and torque.

![Stator](image)

Figure 1: Laminated steel stampings - Stator

Steel laminations in the stator can be slotted or slotless as shown in Figure 2. A slotless core has
lower inductance, thus it can run at very high speeds. Because of the absence of teeth in the lamination stack, requirements for the cogging torque also go down, thus making them an ideal fit for low speeds too (when permanent magnets on rotor and tooth on the stator align with each other then, because of the interaction between the two, an undesirable cogging torque develops and causes ripples in speed). The main disadvantage of a slotless core is higher cost because it requires more winding to compensate for the larger air gap.

**Figure 2: Slotted and slotless motor**

Proper selection of the laminated steel and windings for the construction of stator are crucial to motor performance. An improper selection may lead to multiple problems during production, resulting in market delays and increased design costs.

**Rotor**

The rotor of a typical BLDC motor is made out of permanent magnets. Depending upon the application requirements, the number of poles in the rotor may vary. Increasing the number of poles does give better torque but at the cost of reducing the maximum possible speed.
Another rotor parameter that impacts the maximum torque is the material used for the construction of permanent magnet; the higher the flux density of the material, the higher the torque.

**Working Principles and Operation**

The underlying principles for the working of a BLDC motor are the same as for a brushed DC motor; i.e., internal shaft position feedback. In case of a brushed DC motor, feedback is implemented using a mechanical commutator and brushes. With a in BLDC motor, it is achieved using multiple feedback sensors. The most commonly used sensors are hall sensors and optical encoders.

**Note:** Hall sensors work on the hall-effect principle that when a current-carrying conductor is exposed to the magnetic field, charge carriers experience a force based on the voltage developed across the two sides of the conductor.

*If the direction of the magnetic field is reversed, the voltage developed will reverse as well. For Hall-effect sensors used in BLDC motors, whenever rotor magnetic poles (N or S) pass near the hall sensor, they generate a HIGH or LOW level signal, which can be used to determine the position of the shaft.*

In a commutation system – one that is based on the position of the motor identified using feedback sensors – two of the three electrical windings are energized at a time as shown in figure 4.

In figure 4 (A), the GREEN winding labeled “001” is energized as the NORTH pole and the BLUE winding labeled as “010” is energized as the SOUTH pole. Because of this excitation, the SOUTH pole of the rotor aligns with the GREEN winding and the NORTH pole aligns with the RED winding labeled “100”. In order to move the rotor, the “RED” and “BLUE” windings are energized in the direction shown in figure 4(B). This causes the RED winding to become the NORTH pole and the BLUE winding to become the SOUTH pole. This shifting of the magnetic field in the stator produces torque because of the development of repulsion (Red winding – NORTH-NORTH alignment) and attraction forces (BLUE winding – NORTH-SOUTH alignment), which moves the rotor in the clockwise direction.
This torque is at its maximum when the rotor starts to move, but it reduces as the two fields align to each other. Thus, to preserve the torque or to build up the rotation, the magnetic field generated by the stator should keep switching. To catch up with the field generated by the stator, the rotor will keep rotating. Since the magnetic field of the stator and rotor both rotate at the same frequency, they come under the category of synchronous motor.

This switching of the stator to build up the rotation is known as commutation. For 3-phase windings, there are 6 steps in the commutation; i.e., 6 unique combinations in which motor windings will be energized.

Driving circuitry and waveforms for the implementation of a BLDC motor will be discussed in the second part of this article.

**Torque and Efficiency**
For the study of electric motors, torque is a very important term. By definition, torque is the tendency of force to rotate an object about its axis.

\[ \text{Torque (Newton - meters)} = \text{Force (Newton)} \times \text{Distance (meters)} \]

Thus, to increase the torque, either force has to be increased – which requires stronger magnets or more current – or distance must be increased – for which bigger magnets will be required. Efficiency is critical for motor design because it determines the amount of power consumed. A higher efficiency motor will also require less material to generate the required torque.

\[ \text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} \times 100\% \]

Where,

\[ \text{Output Power} = \text{Torque} \times \text{Angular Velocity} \]
\[ \text{Input Power} = \text{Voltage} \times \text{Current} \]

Having understood the above provided equations, it becomes important to understand the speed vs. torque curve.

![Figure 5: Speed-Torque-Power curve](image)

Following are the takeaways from the graph shown in Figure 5:

- With an increase in speed, the torque reduces (considering the input power is constant).
- Maximum power can be delivered when the speed is half of the “no load” speed and torque is half of the stall torque.

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<th>Applications</th>
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<td><strong>Single-speed</strong> - For single-speed applications, induction motors are more suitable, but if the speed has to be maintained with the variation in load, then because of the flat speed-torque curve of BLDC motor, BLDC motors are a good fit for such applications.</td>
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<td><strong>Adjustable speed</strong> - BLDC motors become a more suitable fit for such applications because variable speed induction motors will also need an additional controller, thus adding to system cost. Brushed DC motors will also be a more expensive solution because of regular maintenance.</td>
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| **Position control** - Precise control is not required applications like an induction cooker and because of low maintenance; BLDC motors are a winner here too. However, for such applications,
BLDC motors use optical encoders, and complex controllers are required to monitor torque, speed, and position.

**Low-noise applications** - Brushed DC motors are known for generating more EMI noise, so BLDC is a better fit but controlling requirements for BLDC motors also generate EMI and audible noise. This can, however, be addressed using Field-Oriented Control (FOC) sinusoidal BLDC motor control.

In the next part of this article, we will address controlling the speed, position, and torque of BLDC motors.

**About the Author**

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Brushless DC Motors--Part II: Control Principles

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Part I - Construction and Operating Principles

Having understood the construction and basic operating principle of BLDC motor in the first part of this article, it becomes important to understand the motor control options available for the reliable operation and protection of motors. Based on the functions served, motor control can be classified into following categories:

- Speed control
- Torque control
- Motor protection

Implementation of these control functions requires monitoring of one or more motor parameters and then taking corresponding action to achieve the required functionality. Before getting into the details of these control function implementations, it is important to understand the implementation of logic and hardware required to build up the rotation of the motor or to establish commutation.

Commutation implementation

As discussed in the previous part of this article, based on the position of the motor (identified using feedback sensors), two of the three electrical windings are energized at a time. To be able to energize the windings, external circuitry is required to be able to meet the current requirements of the motor. A typical control circuit with a 3-phase winding connection is shown in Figure 1. V1, V3, V5 and V2, V4, V6 make a 3-phase voltage source inverter connected across the power supply. V1 and V4 form one bridge. V1 is high side, which is connected to the high voltage DC source while V4 is low side, which is connected to ground.
By adjusting the high-side and low side of the power device (via signals V1H, V3H, V5H and V2L, V4L, v6L), the current flow through the stator winding can be controlled. For example, if current has to flow in to the RED winding and flow out from the BLUE winding, turning on V1 and V6 while keeping the other signals will cause the current to flow in the required direction, as shown in Figure 2 (A). Next, by switching ON V5 and V6 and turning all other signals OFF, the current can be switched to flow in from the GREEN winding and out from the BLUE winding, shown in Figure 2 (B).

Following the same procedure, the 6-step driving sequence for a BLDC motor can be generated. Table 1 provides the switching sequence for power circuitry based on a Hall sensor output.
However, if the rotation has to be reversed, then the sequence needs to be reversed as well. Figure 3 shows the excitation waveform, including phase current, phase voltage, Hall sensor, and sector value. The top half of the figure shows the 3-phase winding excitation current and voltage in which black lines are phase current, while green, red, and blue lines are the phase voltage. As the phase current is trapezoidal, we call 6-step BLDC control trapezoidal control.

The Hall sensor and the excitation have a fixed relationship. Typically, there are two types of Hall sensors. For the first type, for each HALL phase, their waveforms have a 60-degree time-lapse. For the second type, the waveform time-lapse is 120 degrees.

With a basic understanding of commutation, let us now switch to the implementation of control functions, which are critical for any motor design.
Speed control

Following the commutation sequence in a given order helps in ensuring the proper rotation of the motor. Motor speed, then, depends upon the amplitude of the applied voltage. The amplitude of the applied signal is adjusted by using pulse width modulation (PWM). Figure 4 shows the switching signals for various power devices.

![Figure 4: Switching signals of Power devices](image)

It can be noted from the above diagram that the higher side transistors are driven using PWM. By controlling the duty cycle of the PWM signal, the amplitude of the applied voltage can be controlled, which in turn will control the speed of the motor. To be able to achieve the required speed smoothly, the PI control loop is implemented as shown in Figure 5.
The difference between the required speed and the actual speed is input into the PI controller, which then modulates the duty cycle of the PWM based on the error signal obtained by the difference between the actual speed and required speed.

Torque control

Torque control is important in various applications where at a given point of time, the motor needs to provide a specific torque regardless of the change in load and speed at which the motor is running. Torque can be controlled by adjusting the magnetic flux, however flux calculations require complex logic. However, magnetic flux is dependent upon the current flowing through the windings. Thus, by controlling current, torque of a motor can be controlled.

![Torque control diagram]

Figure 6 shows the torque control implementation logic. By maintaining the current flowing through the windings, torque can be controlled. A PI loop similar to that used to control speed can be implemented to smooth the torque response curve with changes in load.

Motor Protection

In a motor control design, it is important to have protection logic to ensure safe operation of the system. For example, when the motor get stuck, the current through the windings can build up to a very high level, which can burn the power devices driving the motor.

Peak current: This is the maximum instantaneous current allowed to flow through the windings for safe operation. This condition occurs in case of a short circuit. Hardware protection is applied to kill the PWM output whenever the current crosses the peak current limit.

Maximum Working Current: This is the maximum output current when the motor stalls or is overloaded. This current can be controlled by application firmware. Implementation for this logic is similar to torque control.
**Under Voltage** - When the system is running on batteries, it becomes important to cut off the supply if the battery voltage drops below a particular limit. Since voltage drop is a slow process, it can be controlled via firmware.

**Hall Sensor Failure** - In sensor-based BLDC motors, rotation of the motor is based solely on the feedback obtained from the Hall sensors. Thus, in case of failure of the Hall sensors, the commutation sequence will break, which may cause the BLDC motor to become stuck and the current to rise above a particular limit. Hall sensor failure can be detected in firmware by checking whether the hall sensor signal changes its logic level or not. If it gets stuck to a particular level, then it can be detected as a failure and the motor drive can be disconnected, letting it run on inertia or be stopped by applying the brake. The action to be taken depends on the requirements of the design.

There are controllers available in the market which can do BLDC motor control. With the advent of System-On-Chip (SOCs) controllers, the complete control logic for implementing BLDC motor control can be implemented within a single device. This not only helps in reducing the cost but such integration provides flexibility to enable designers to manage control of the system according to application-specific requirements.

Figure 7 shows the design of a motor control system using Cypress’s flagship controller Programmable System on Chip (PSoC) – CY8C24533. In this design, which uses a Hall sensor input the commutation sequence is controlled by generating PWM signals. This device has a built-in ADC, amplifier (PGA), and comparator (CMP), which are used to measure voltage and current for the implementation of speed and torque control. The PI control loop is implemented in firmware to execute on the CPU. For over current protection, the comparator (CMP) is used to kill the PWM output in case of over current. CMP blocks available inside the device provide an internal programmable threshold voltage for use in accommodating for motors across a wide range of
currents. This device also provides access to communication blocks which can be used to implement communication protocols like UART, SPI, and I2C to transmit debug / control data to the host controller.

This article provides the basic implementation of BLDC motor control system for speed and torque control. It also discusses the importance of protection logic and how to implement the same in a given system.

About the Author

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