Brushless DC Motors – Part I: Construction and Operating Principles

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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.

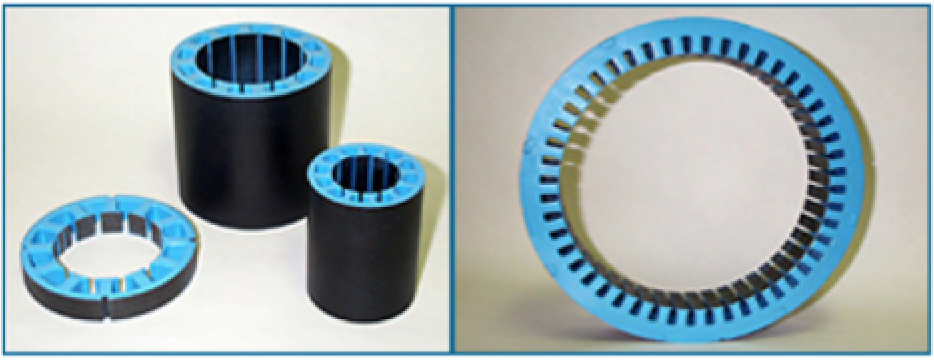

Figure 1: Laminated steel stampings - Stator

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.

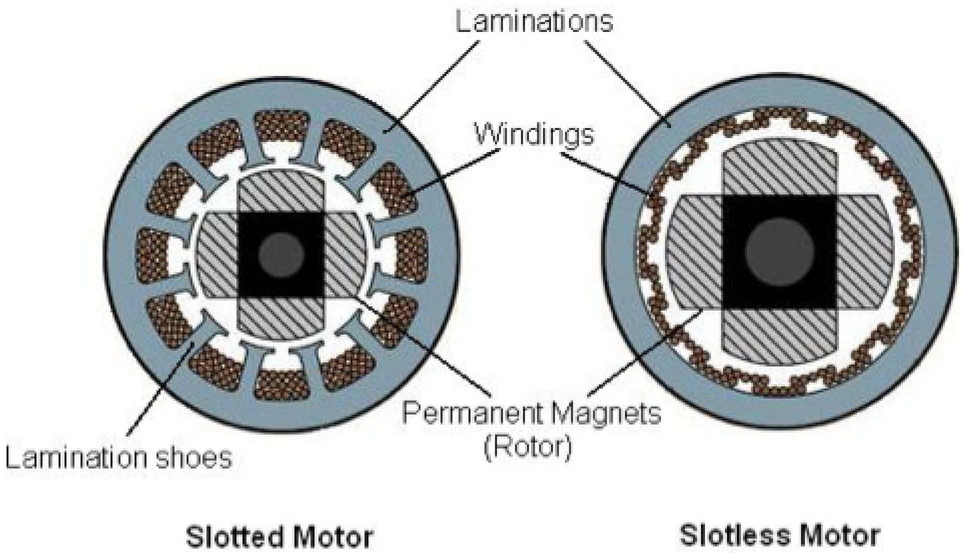

Figure 2: Slotted and slotless motor

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.

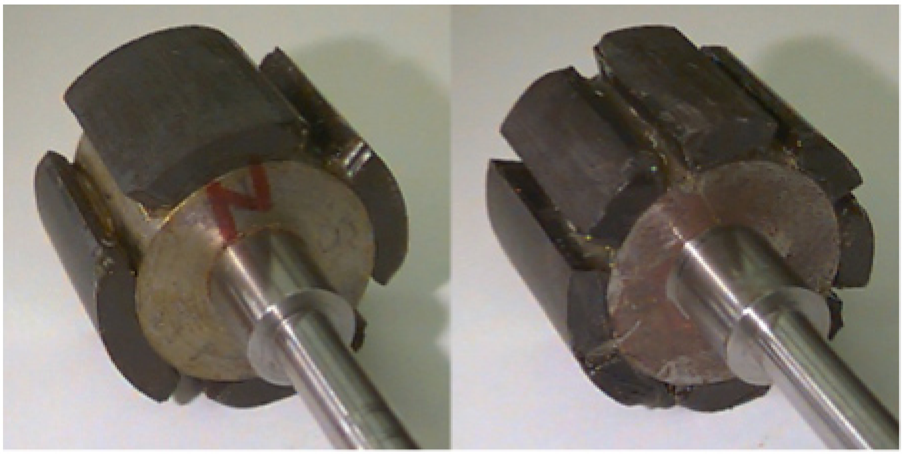

Figure 3: 4 pole and 8 pole – Permanent magnet rotor

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.

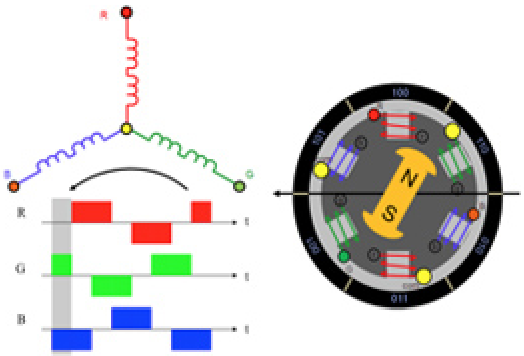

Figure 4(A): Phase 1

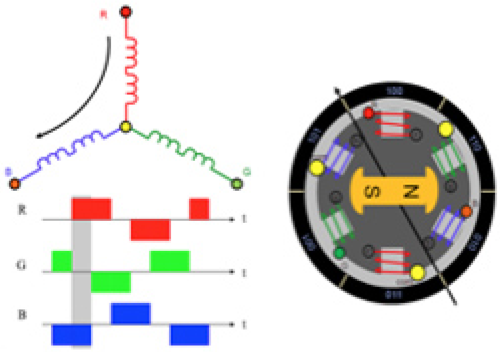

Figure 4(B): Phase 2

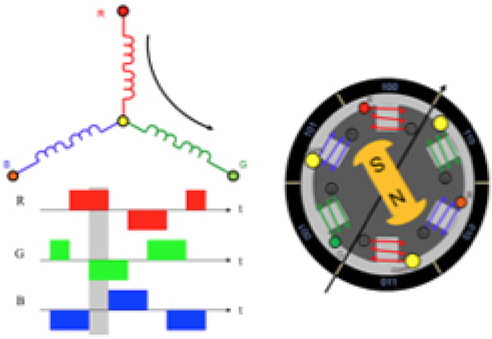

Figure 4(C): Phase 3

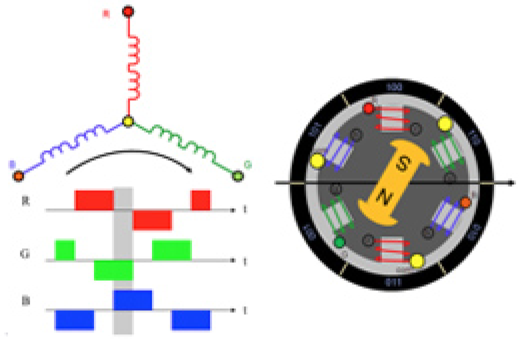

Figure 4(D): Phase 4

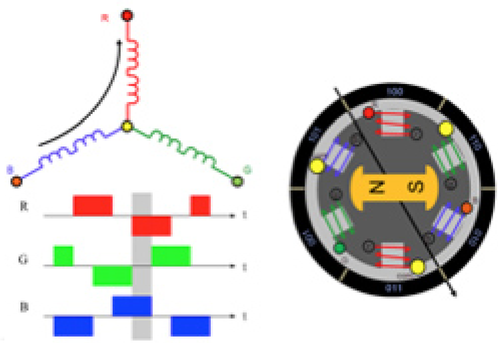

Figure 4(E): Phase 5

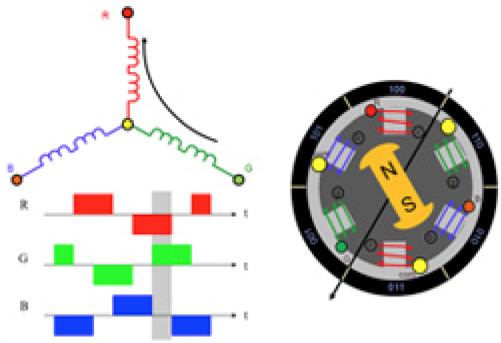

Figure 4(F): Phase 6

Torque and Efficiency
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 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.

$$Torque\ (Newton - meters) = Force\ (Newton)\ X\ Distance\ (meters)$$

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.

$$Efficiency = \frac{Output\ Power}{Input\ Power}\%$$

Where,

$Output\ Power = Torque\ X\ Angular\ Velocity$, and

$Input\ Power = Voltage\ X\ Current$

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

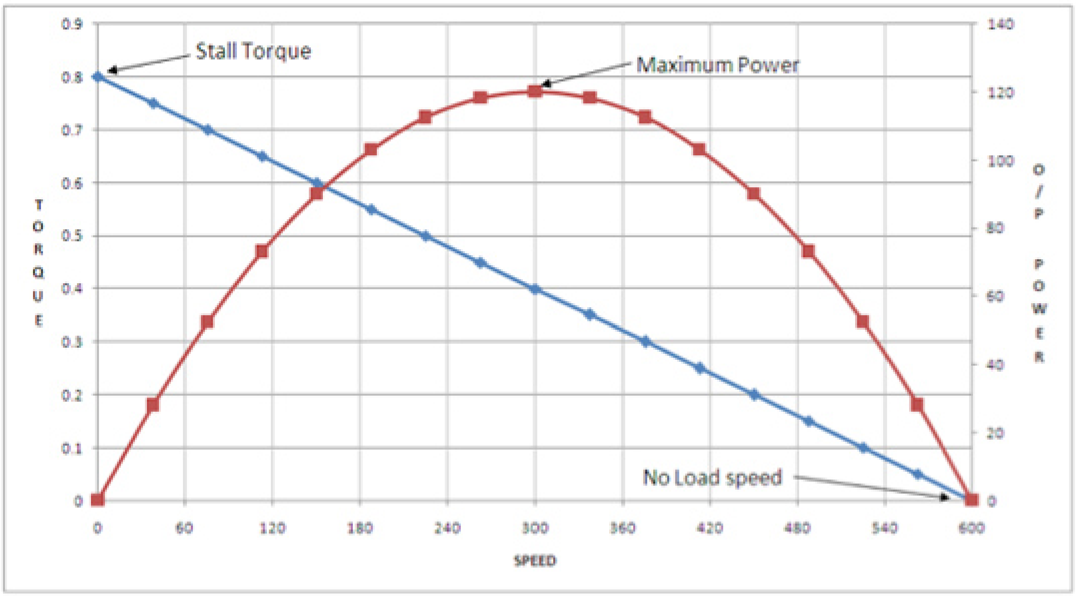

Figure 5: Speed-Torque-Power curve

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.

Comparison of BLDC motor with other motors

Feature	Brushless DC motor	Brushed DC motor	Induction Motor
Mechanical Structure	Field magnets on the stator and rotor are made of permanent magnets	Field magnets on the rotor and stator are made of permanent magnets or electromagnets	Both the rotor and stator have windings but the AC lines are connected to the stator
Maintenance	Low or no maintenance	Periodic maintenance because of brushes	Low maintenance
Speed-Torque characteristics	Flat – Operation at all speeds with rated load	Moderate – Loss in torque at higher speeds because of losses in brushes	Non-linear
Efficiency	High – No losses in the brushes; Stator is on the outer periphery and is thus able to dissipate more heat and produce more torque	Moderate – Losses in the brushes; Rotor is on the inner periphery	Low – Heat and current losses in both rotor and stator; High efficiency Induction motors are also available (higher cost)
Commutation method	Using solid state switches	Mechanical contacts between brushes and commutator	Special starting circuit is required
Speed range	High – No losses in brushes	Moderate – Loses in brushes	Low – Determined by the AC line frequency; Increases in load further reduces speed
Electrical noise	LOW	High – Because of brushes	LOW
Detecting method of rotor's position	Hall sensors, optical encoders, etc.	Automatically detected by brushes and commutator	NA
Direction reversal	Reversing the switching sequence	Reversing the terminal voltage	By changing the two phases of the motor input
Control requirements	A controller is always required to control the commutation sequence	No controller is required for a fixed speed; controller required for variable speed	No controller is required for a fixed speed; controller required for variable speed
System cost	High – Because of external controller requirement	Low	Low

Applications

Single-speed – 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.

Adjustable speed – 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.

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.

Also see:

- Implement efficient control of multiple Brushless DC motors
- Field-oriented control by the numbers
- BLDC motor control for respirators
- Modular Approaches to Brushless DC Motor Drives
- Implementing Embedded Speed Control for Brushless DC Motors
- Designing a MCU-driven permanent magnet BLDC motor controller

In the next part of this article, we will address controlling the speed, position, and torque of BLDC motors. Click here to read part 2.

About the Author
Pushek Madaan *is currently working with Cypress Semiconductor India Pvt. Ltd. as a Senior Application Engineer. His interests lie in designing Embedded system applications in C and assembly languages, working with analog and digital circuits, developing GUIs in C# and, above all, enjoying adventure sports. Pushek can be reached at pmad@cypress.com.*