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.

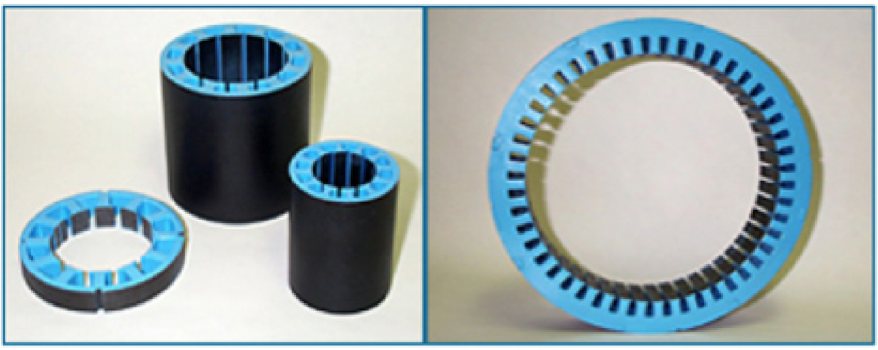

Figure 1: Laminated steel stampings - Stator

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.

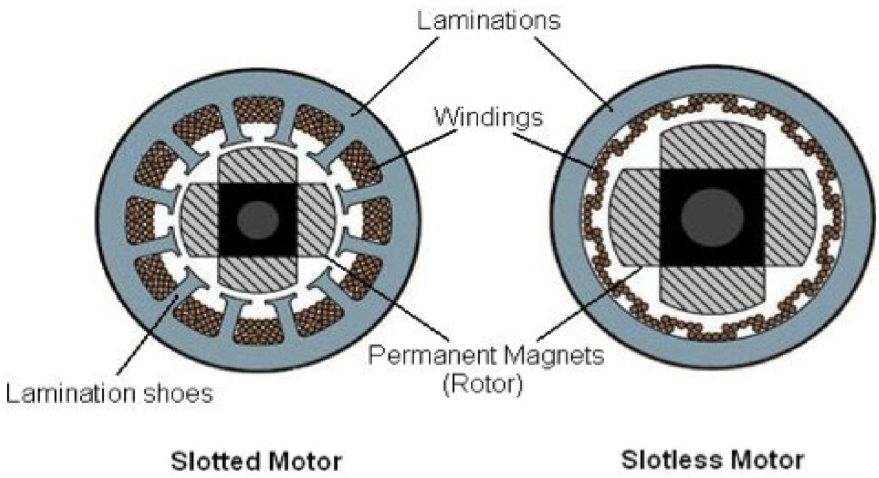

Figure 2: Slotted and slotless motor

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.

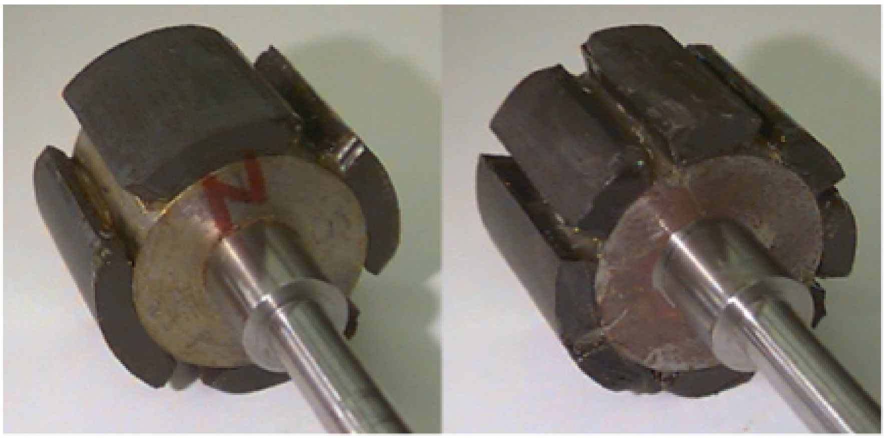

Figure 3: 4 pole and 8 pole – Permanent magnet rotor

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.

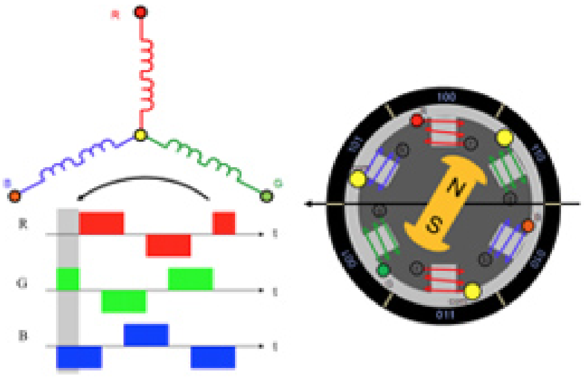

Figure 4(A): Phase 1

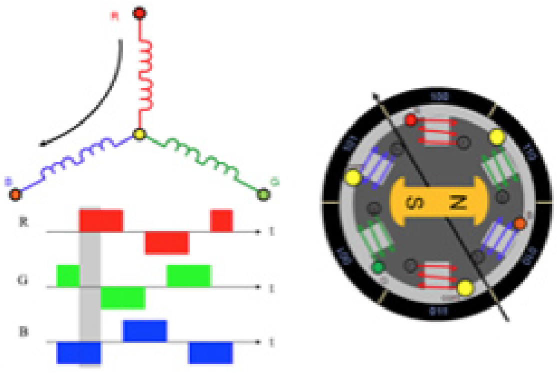

Figure 4(B): Phase 2

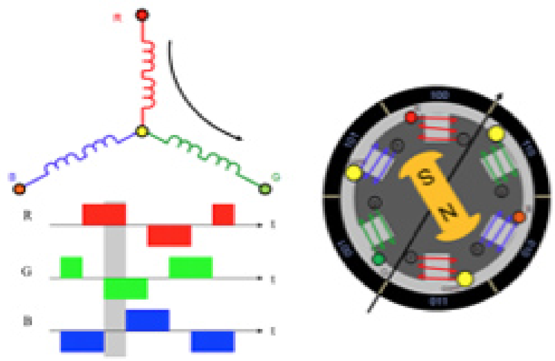

Figure 4(C): Phase 3

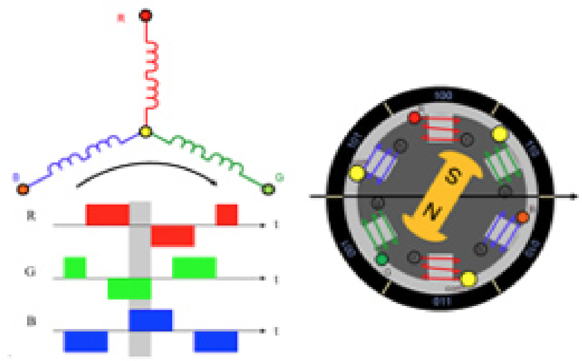

Figure 4(D): Phase 4

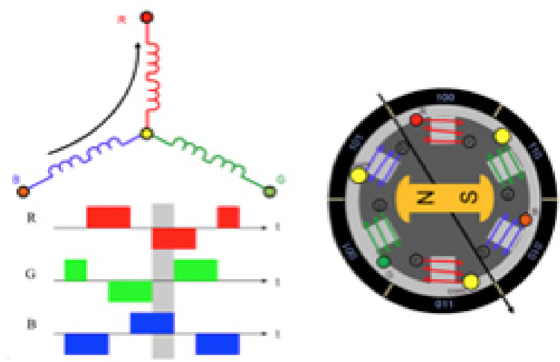

Figure 4(E): Phase 5

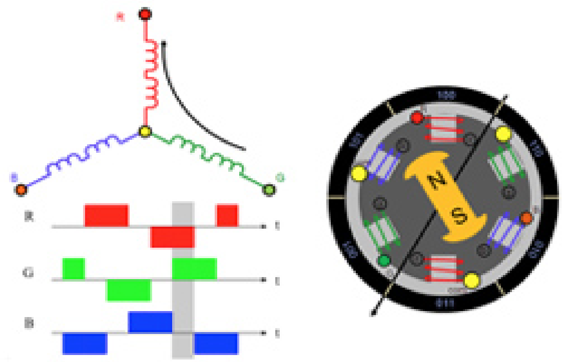

Figure 4(F): Phase 6

Brushless DC Motors--Part II: Control 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.

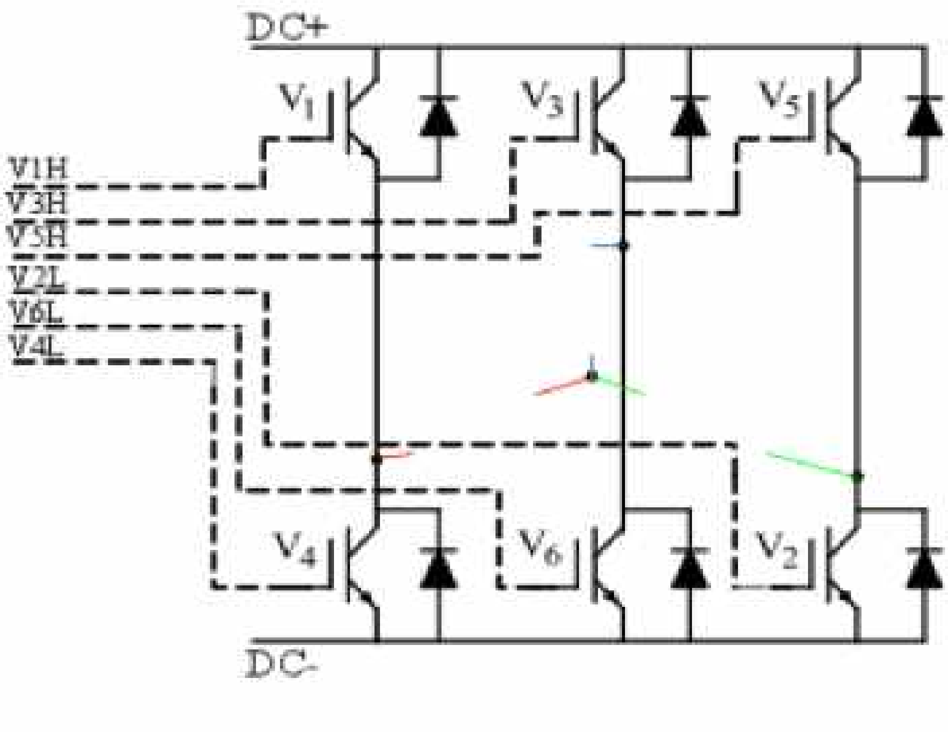

Figure 1: Control circuit for 3 phase BLDC windings

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).

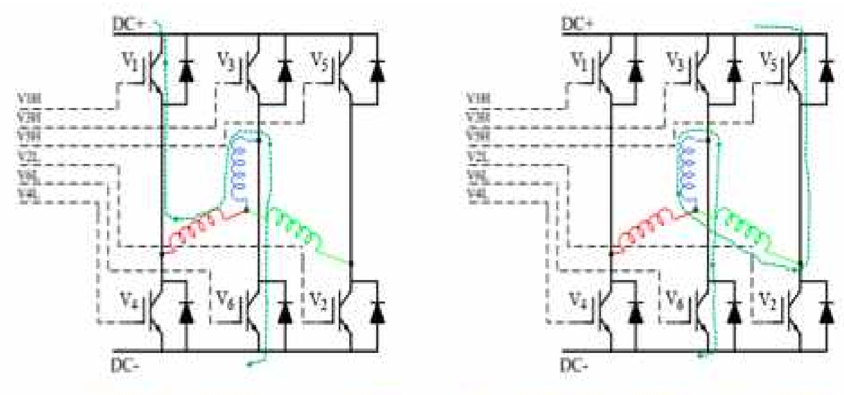

Figure 2 (A) – V1 and V6 ON; remaining all OFF

Figure 2 (B) – V5 and V6 ON; remaining all OFF

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.

Table 1: Switching sequence

Hall C	Hall B	Hall A	Green	Red	Blue	Sector No.	MOSFET - ON
0	0	1	DC+	NC	DC-	0	V5, V6
0	1	1	DC+	DC-	NC	1	V4, V5
0	1	0	NC	DC-	DC+	2	V3, V4
1	1	0	DC-	NC	DC+	3	V2, V3
1	0	0	DC-	DC+	NC	4	V1, V2
1	0	1	NC	DC+	DC-	5	V1, V6

To build up the rotation, the motor should be periodically switched from one phase to another as shown below.

→ 0 → 1 → 2 → 3 → 4 → 5 ↩

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.

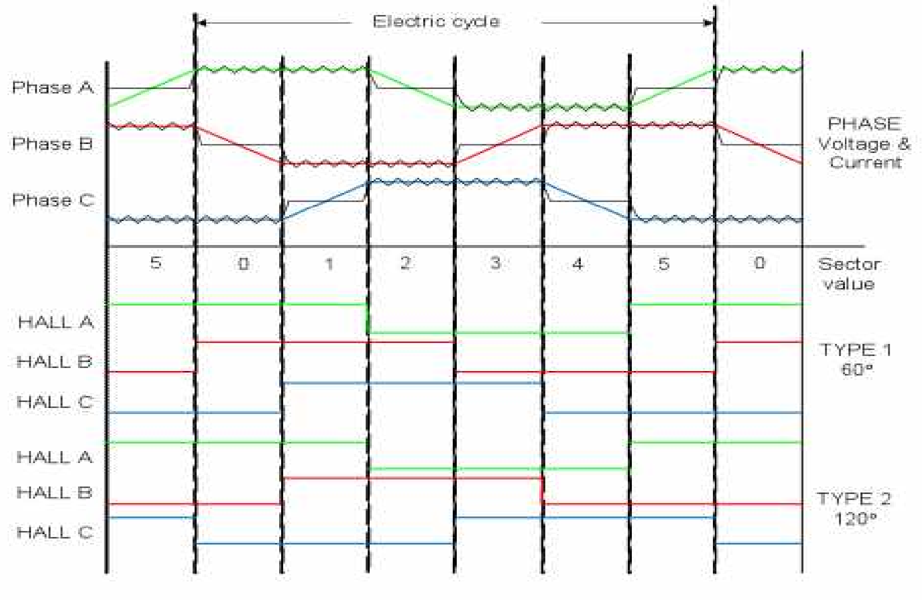

Figure 3 – Voltage and current through the windings

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.

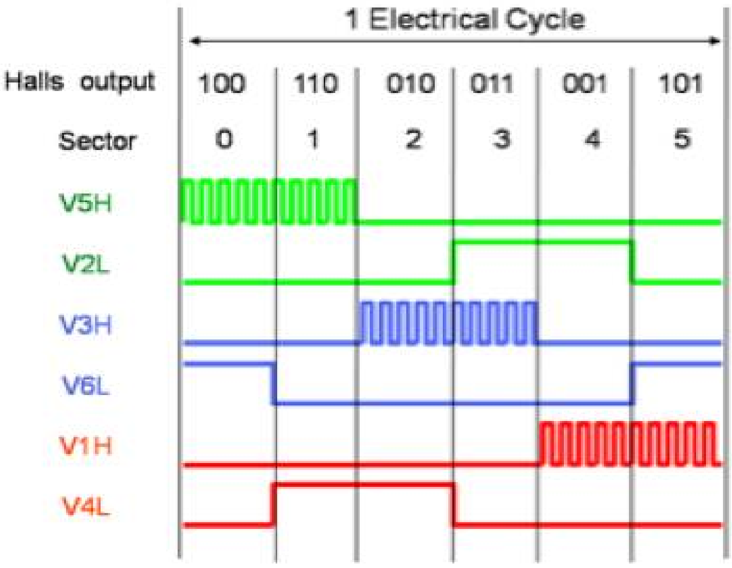

Figure 4: Switching signals of Power devices

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.

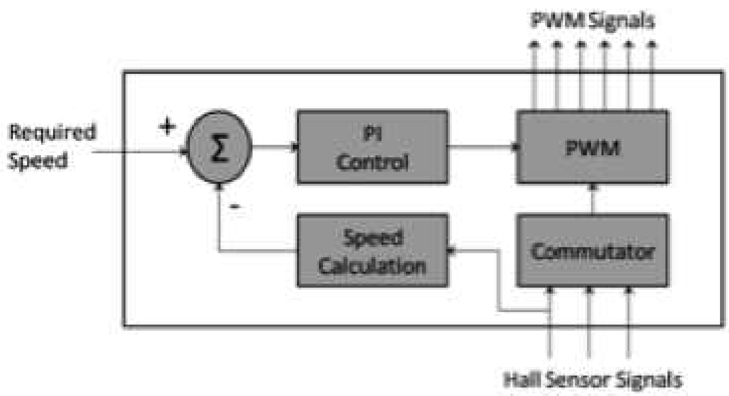

Figure 5: Speed control loop