# AN1164

# Introduction to Brushless DC Motors

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Due to their superior efficiency, excellent controllability, and higher speed capabilities, brushless DC motors (BLDC) are one of the most widely used DC motors. These characteristics make BLDC suitable for many kinds of applications in a large variety of industries.

Nowadays, BLDC motors are nearly everywhere and have a solid role in manufacturing and industrial applications as actuators and in CNC machine tools. Similarly, its efficiency has made it a popular choice for white goods, computer hard drives, electric and hybrid vehicles, and even medical equipment.

In the automotive industry, its presence is expected to increase due to the growing number of electromechanical in-vehicle systems, including HVAC systems, fuel and water pumps, anti-lock braking systems (ABS), and power steering systems.

This application note explains the main features of brushless DC motors, their control methodology, and how different aspects between BLDC and BDC motors compare.

## Structure

A brushless DC motor is composed of two main parts: the rotor and the stator.

### Stator

The stator carries the windings of the motor unlike brushed DC motors; coils are not in the rotor but are wound and fixed to the stator. Wires are wrapped around laminated steel arms or teeth, forming stator windings. Windings can be arranged in two configurations: concentrated and distributed. These two differ in the way the coils are wound around the stator and the waveform of its back-EMF.

In a concentrated winding, each phase is wound around a stator arm and gives a trapezoidal back-EMF waveform. As its name suggests, distributed winding has phase coils distributed along multiple arms, giving a sinusoidal back-EMF output. A sinusoidal back-EMF reduces torque ripple but involves extra copper windings.

### Rotor

The rotor consists mainly of a shaft and a permanent magnet with alternating magnetic poles. The number of poles in the rotor depends on the application. Having more poles can improve torque but reduce maximum speed.

Ferrite magnets are commonly used in the rotor, but rare-earth magnets have significantly taken over this role, especially in electric vehicles because of their greater power density at a much smaller size, offering a lighter and more compact motor design.

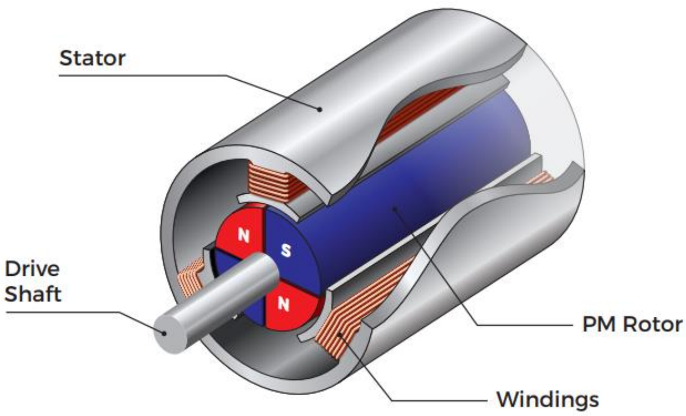


**Figure 1. Axial view of a Brushless DC motor**

**Inner rotor design or *inrunner***

The majority of BLDC motors use the arrangement where the permanent magnet rotor is inside a wound stator. The two main advantages are high heat dissipation efficiency due to the windings' position, and the ability to minimise the overall girth of the motor unit. However, high energy magnets need to be used and could have an impact on cost. Because of its low inertia, the inrunner design is suitable for high-speed applications, such as fan-jets, RC cars, and electric vehicles.

**Outer rotor design or *outrunner***

In this set-up, the external rotor is housing the stator and is larger than in a conventional motor. This provides a higher moment of inertia and reduces the ripple torque delivering a smooth rotation at low speeds. This design is commonly found in high-torque applications, such as pumps and fans (since the rotor housing can act as a hub).

**Figure 2. Inrunner (left) and Outrunner (right) BLDC motor**

## Single and three-phase BLDC motor

There are three types of BLDC motors: single-phase, two-phase, and three-phase. The number of phases is determined by the number of stator windings. The single-phase and three-phase motors are the most commonly used.

**Single-phase**

The stator of a single-phase motor has one set of windings around four stator arms, resulting in two pairs of electromagnetic poles when energised. Its simple structure makes it smaller compared to a three-phase motor. However, a single-phase BLDC motor can only turn in one direction. For this reason, it is generally used in pump and fan applications.

**Three-phase**

Three-phase motors have three sets of windings in the stator and are able to turn clockwise and counter-clockwise. Having three phases allows the windings to be connected in two different configurations: star and delta connection. However, the delta connections can be considered inefficient for driving a brushless DC motor, which is why most BLDCs are star connected. Compared to a single-phase, this option is slightly higher in cost, but that is greatly compensated with improved control and smoother running.

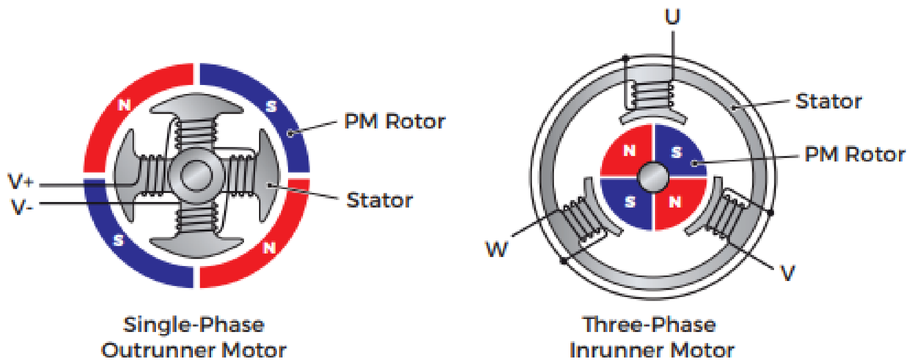


**Figure 3. Single-phase and three-motor**

## Poles

A pole pair in a BLDC motor can refer to the electromagnetic poles on the stator or the magnetic poles on the rotor. The most basic three-phase BLDC has three-pole pairs on the stator and can accommodate multiple poles on the rotor, depending on the application.

Pole count affects the performance of a motor. More rotor poles demands more frequent switching cycles within a mechanical revolution due to the necessity of a 90° angle to provide maximum torque between the magnetic field of the rotor and stator. Thus, as the pole count increases, the electromagnetic torque in the motor will be greater and the maximum speed will be reduced.

## Commutation

As its name implies, BLDC motors do not use brushes for commutation. Since the coils are static, there is no need of a mechanical commutator to energise the windings. Instead, the commutation is done electronically, usually via a microcontroller unit and semiconductor switches.

Electronic commutation consists of a series of steps where current from an external drive circuitry is delivered to each phase coil in a controlled sequence, producing a proper motor rotation by magnetic interaction between rotor and stator.

To achieve this in a three-phase motor, current flows into one of the windings, goes through a common node, and flows out from another; leaving a third one open circuit. That way, when a rotor pole is about to align with its electromagnetic counter-pole on the stator, this is turned off and the next phase turned on, which makes the rotating motion continuous.

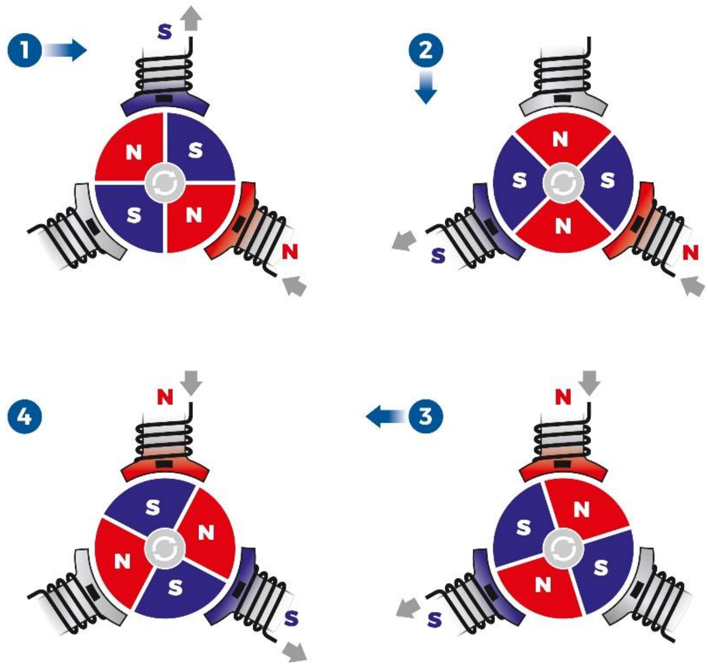


**Figure 4. Electronic commutation by energised windings**

The key part of this process is always keeping track of where the rotor is with respect to the stator so that the right phase can be excited at the right time. This is known as **position feedback**, which can be achieved with the aid of sensors or by reading the back-EMF produced in the windings.

Electronic commutation can be sensored or sensorless depending on the means to estimate the rotor position.

**Sensored commutation**

The easiest and most common way to achieve electronic commutation is by using Hall-effect sensors for position feedback. These are located on the stator at 120° apart from each other in three-phase motors. Every time a rotor pole passes near a sensor, it will output a logic signal HIGH (for N-pole) or LOW (for S-pole), thus detecting the position of the rotor. These signals are then read by a microcontroller and sent to electronic switches in a driver circuit, allowing current to flow into the coils respectively and guaranteeing a proper commutation. Optical encoders are often coupled with Hall-effect sensors when a more precise position-tracking is needed. Using encoders not only offers better accuracy, but also speed and direction readings.

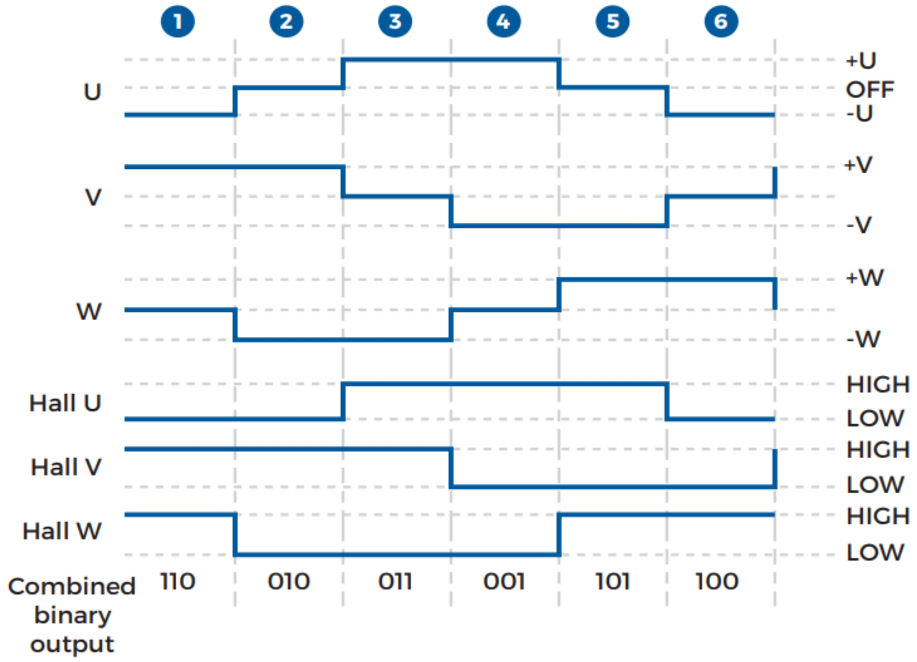


**Figure 5. Phase excitation and Hall-sensor outputs**

A complete mechanical revolution is achieved after the sixth logical combination of the Hall-sensor outputs.

**Sensorless commutation**

As the rotor turns, voltage known as back-EMF is induced in the windings and opposes the supplied voltage. This resembles the behaviour of a generator, making this induced voltage proportional to the angular velocity of the rotor. Back-EMF is read from the non-energised coil in the commutation cycle, obtaining position and speed of the rotor at once. This technique is sometimes called trapezoidal commutation because of the back-EMF waveform.

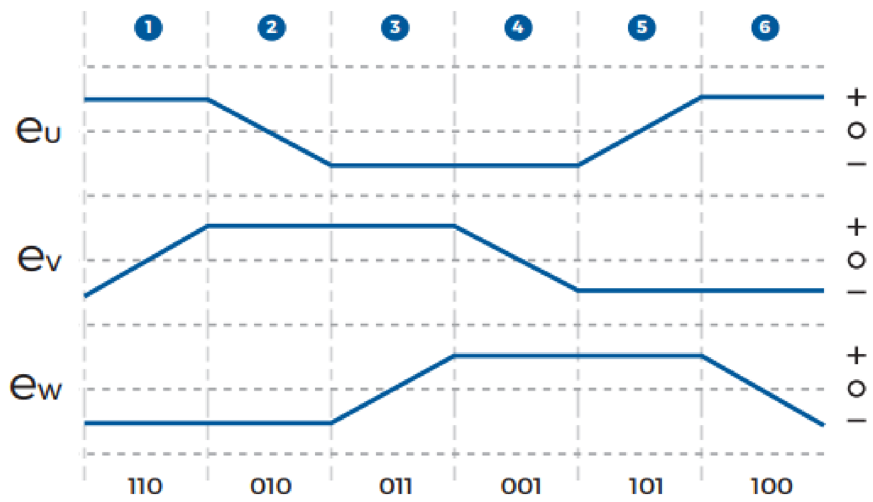


**Figure 6. Phase excitation and respective back-EMF**

Despite its high accuracy and cost-saving characteristics, sensorless commutation comes with some drawbacks.

A minimum back-EMF is needed to properly execute commutation. This means that when the rotor is stationary, the motor is not able to start since no back-EMF is produced. Similarly, the induced back-EMF at low speeds might not satisfy the minimum speed required, resulting in a poor commutation.

A common solution is to drive the motor through an initial open-loop stage where it is “freely” accelerated up to a minimum speed where the control algorithm can keep up with the commutation. Other solutions involve a pre-positioning step, initial position detection of the rotor with a microcontroller, or reading the line-to-line voltage difference to amplify the back-EMF.

## Control

A DC motor can be controlled by varying the voltage applied to its phase terminals. For this purpose, a digital control technique called pulse width modulation (PWM) is used. This technique regulates the voltage by switching on and off the power supply at a high frequency. By varying the ratio between on-time over a certain period, an average voltage can be calculated This ratio is known as the duty cycle. Since the speed of the motor is proportional to its applied voltage; the higher the duty cycle is, the faster the motor will rotate. PWM is an efficient solution to create a power analog output using semiconductor switches. A microcontroller is normally used to generate PWM, but it can also be done with dedicated IC motor controllers.

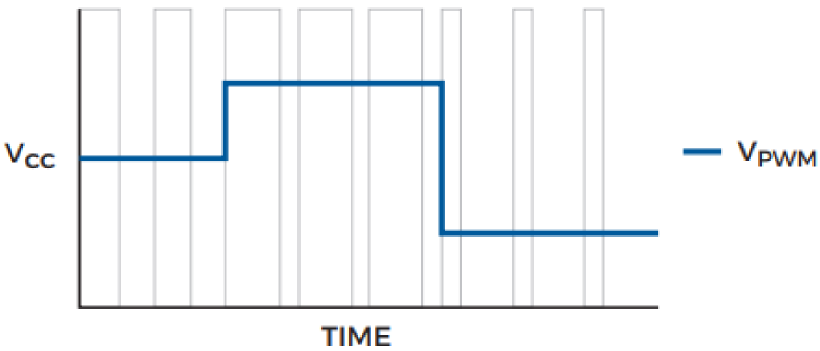


**Figure 7. Relationship between wave duty cycle and PWM output voltage**

A driver circuit is essential when it comes to controlling a DC motor. These circuits allow the controller to adjust the direction of the motor, thus playing an important role in commutation. In the case of a **single-phase** motor, an inverter circuit called the “H-Bridge” is used; comprised of four electronic switches (two high-side and two low-side) to allow bidirectional rotation based on the direction of the current flowing through the circuit.

The simplest drive mode for an H-Bridge is the sign/magnitude drive, where only one side of the circuit is driven with a PWM signal while the other remains on. An advantage of this method is that since only two transistors are PWM’ed for bidirectional rotation, less PWM inputs are necessary to drive the motor. To change the driving direction, the PWM side and the constant signal side are swapped.

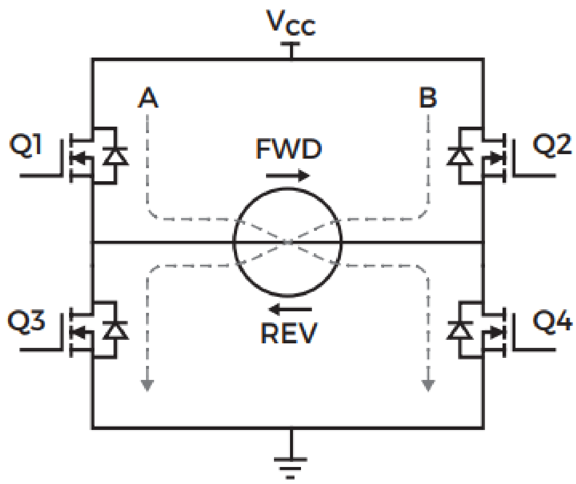


**Figure 8. H-bridge inverter circuit**

If Q1 and Q4 are closed, current will flow through path “A”, making the motor rotate in the forward direction. Whereas if Q2 and Q3 are closed, current will flow through path “B” and the motor will rotate in the reverse direction.

If Q3 and Q4 are closed, the motor is short-circuited to ground and will enter a braking state. Because the voltage through the motor is 0V, it can only slow down until completely stopping. The same applies when Q1 and Q2 are closed.

If all switches are left open, the motor will be in a coasting state; spinning freely until frictional resistances slow it down.

| | **Forward** | **Reverse** | **Coasting** | **Braking** |
|---|---|---|---|---|
| **Q1** | On | Off | Off | Off |
| **Q2** | Off | On | Off | Off |
| **Q3** | Off | On | Off | On |
| **Q4** | On | Off | Off | On |

In the case of a **three-phase** motor, three half-bridge circuits are necessary. While the complexity of this circuit scales up, it follows the same principle as before. Six power MOSFETs are used as switches in this arrangement and each phase of the motor is driven by a pair of high-side and low-side switches.

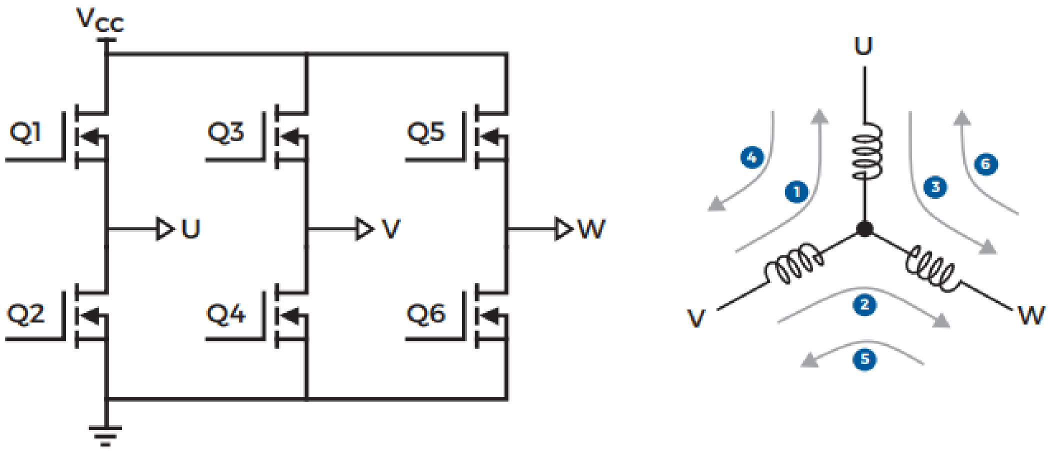


**Figure 9**. **Three Half-Bridges with common node coils**

According to the commutation logic, only two motor windings are excited and one is left floating. As shown in Figure 9 when Q1 and Q6 are ON (Step 3); current from power supply flows into Phase U, energising it positively. Then, through a common node, the same current reaches Phase W and flows out to ground, causing the winding to be negatively energised.

A PWM signal is sent to each phase following a unique combination dictated by the outputs of the Hall-effect sensors or back-EMF readings.

The figure below shows each phase driven by PWM according to the commutation logic in Figure 5. Note that a phase is positive only when it is excited with PWM; in other words, current is flowing in. If both figures are overlaid, the PWM signal would represent the HIGH state of each phase.

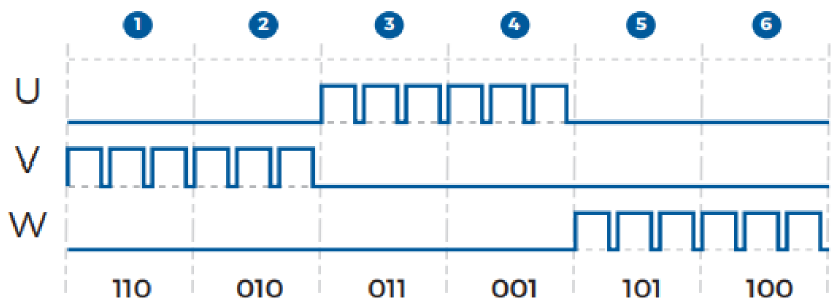


**Figure 10. PWM input applied to each phase**

Most of the time, the output voltage and current from a microcontroller GPIO are limited (3.3V, 10mA - 20mA) and not enough to drive electronic switches directly. In this case, a circuit known as a gate driver is needed. Gate Drivers manage low-power inputs and amplify them to produce an appropriate voltage and current to drive the gate of a power MOSFET.

The control and commutation of a brushless DC motor go hand-in-hand. The switching of the driver circuit is performed by logic outputs from a microcontroller product of the position feedback. The diagram of a BLDC motor control would look similar to the figure below.

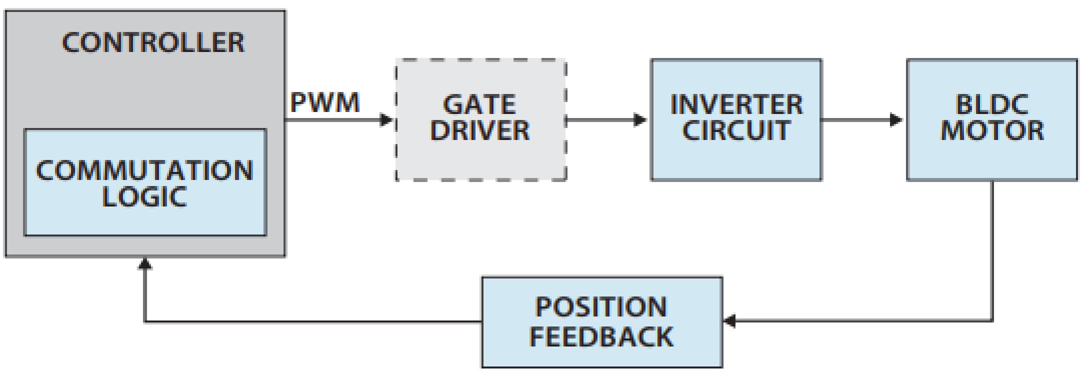


**FIGURE 11. Basic control diagram of a brushless DC motor**

## Comparison Table: BDC vs. BLDC

The following table shows a brief comparison between some of the main characteristics of BDC and BLDC motors.

| | BDC | BLDC |
|---|---|---|
| **Structure and design** | • Composed of rotor, stator, commutator, and brushes.<br>• Stationary magnetic field, rotating coils.<br>• Rotor is encased by the stator | • Composed of rotor and stator<br>• Stationary coils, rotating magnetic field.<br>• Offers inrunner and outrunner designs |
| **Speed range** | • Moderate: maximum speed is limited by mechanical friction and wear of brushes | • High: speed is limited by standard voltage, current, and magnetic field strength relation |
| **Commutation** | • Done with a segmented commutator and carbon brushes | • Done electronically with power semiconductor switches |
| **Control method** | • No control required for fixed-speed unidirectional applications<br>• Bidirectional motion requires an H-Bridge<br>• Speed is controlled by PWM | • Three half-bridges are required for three-phase motor<br>• Control algorithms can be trapezoidal, sinusoidal, or Field-Orientated Control |
| **Control implementation** | • Simple and inexpensive | • Complex and expensive because of external controllers |
| **Durability and reliability** | • Short lifetime<br>• Periodic maintenance due to brush and commutator wear<br>• Contamination issues due to carbon dust from brushes or copper strands from commutator | • Long lifetime<br>• Low to no maintenance is needed<br>• No risk of disturbance caused by contamination |
| **Heat dissipation** | • Poor: heat concentration in the internal rotor | • Great: heat generation in external stator, easier cooling |
| **Cost** | • Low: minimal amount of external components | • High: use of strong permanent magnets and external controller |
| **Ideal when-** | • Low overall cost, simplicity, and over-efficiency are a priority | • Efficiency, controllability, and longevity are a priority |

## Conclusion

Brushless DC motors offer a high-efficiency alternative to brushed DC motors. The removal of a physical commutation system not only gives a greater power-saving advantage but also a better overall performance-to-size ratio, making it ideal for limited-space applications.

Although its control method involves a more complex implementation, the electronic costs have come down significantly. Moreover, the wide speed range and longevity of brushless DC motors make them a better choice over common brushed DC motors for continuous high-speed applications