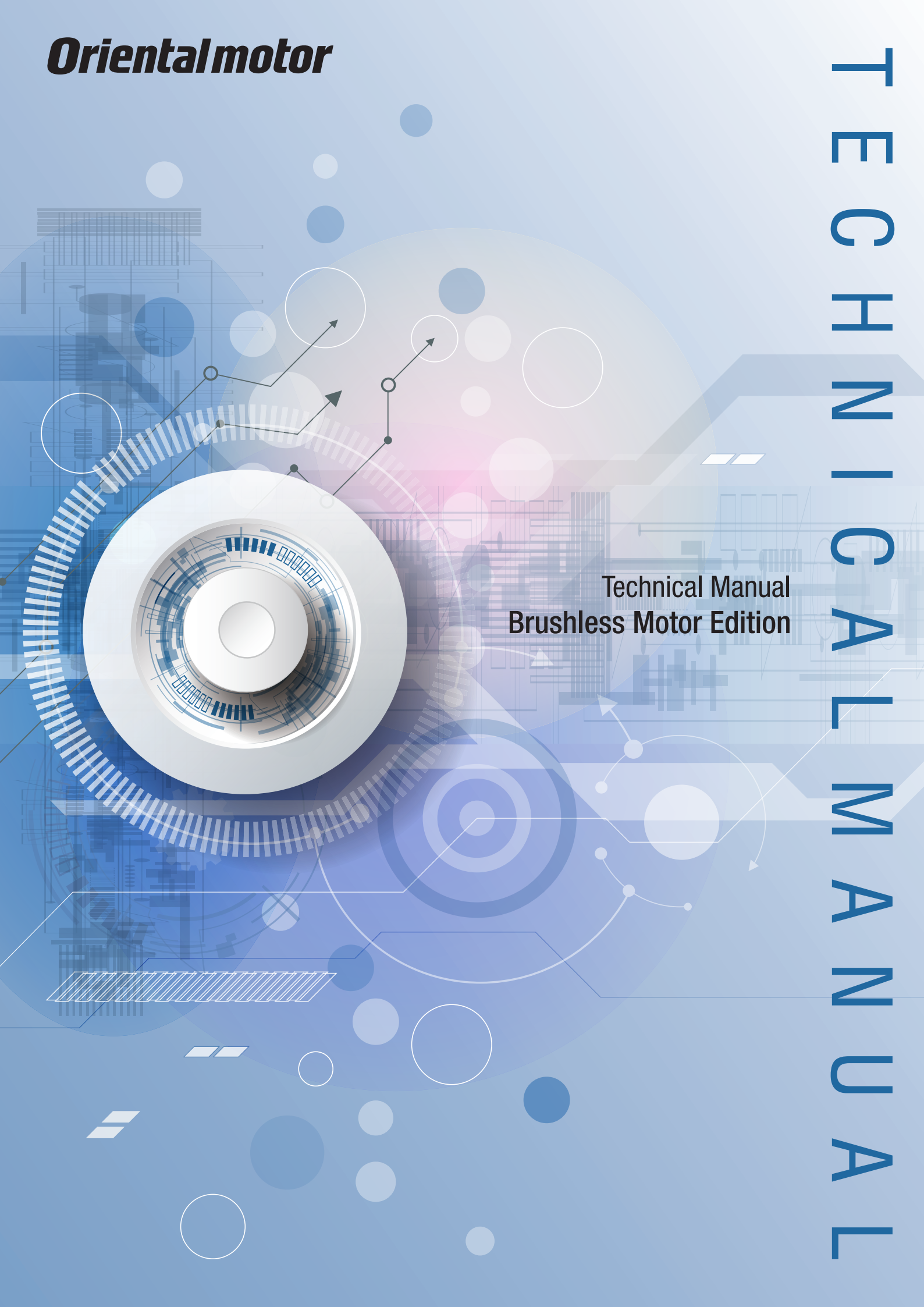


***Orientalmotor***

TECHNICAL MANUAL

Technical Manual  
Brushless Motor Edition





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# Preface

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Motors are used to support every aspect of our daily lives, from our homes to commercial facilities, restaurants, cars, factories, and so on. We rarely see them directly, but when it comes to mobile objects, a variety of motors with different functions and capabilities are used. This technical manual will focus on explaining one type of motor in particular: Brushless DC motors.

Brushless DC motors are excellent in terms of speed controllability and energy conservation. Compared to using inverters and firing angle control to control the speed of induction motors, these motors can be used at a wide range of speeds, from low speed rotation to high speed rotation. In addition, permanent magnets are used in the rotor, and because there is no need to induce current into the rotor as with induction motors, brushless DC motors are compact and offer high output power and efficiency.

However, due to the need for permanent magnets in the rotor, magnetic pole sensor, and a dedicated drive circuit, brushless DC motors were expensive and had limited applications.

In recent years, the development of electronic devices along with increased integration of electronic parts has reduced both the cost and size of drive circuits. Moreover, because the demand for energy conservation has increased in order to address global warming, brushless DC motors have become widely used in energy-saving appliances such as air conditioners, refrigerators, and washing machines, as well as in drive motors and on-vehicle electric motors for electric cars and hybrid cars.

Their compact size and high output power have allowed them to be used for a wide variety of applications, including cooling fans for touch-screen panel computers, disk drive devices, and drones.

This technical manual aims to help readers understand the principles and characteristics of brushless DC motors, as well as serve as a reference to aid in the proper use of AC speed control motors, inverters, and other motors used for speed control.

Before proceeding to the main text, let us briefly touch upon the history of the brushless DC motor and its precursor, the DC motor.

The first motors began as simple concentrated coil windings that utilized electromagnets. Later, due to the development of permanent magnets, with ferrite magnets being the most typical, most compact DC motors began using permanent magnetic fields as opposed to electromagnetic fields, and these are still widely used today.

To address the issue of arc generated between the brushes and commutator in a DC motor, as well as maintenance and life span concerns, there has always been the idea of replacing the mechanical contact of the brush and commutator with an electronic circuit. However, because power electronics technology did not exist, it was not possible to sufficiently adjust the timing of the excitation switching. In the 1960s, due to advances in electronics, a commutator-less motor that replaced the brushes and commutator with transistor switching was created. Various trade names were considered for this type of motor, with "brushless DC motor" and "electronically commutated motor" eventually coming to the fore along with improved characteristics as well as an updated structure and shape. However, the principles behind this motor are the same as those behind the synchronous motor, and the distinction between these has become unclear.

"Brushless DC motors" can utilize both AC and DC power supplies. Because the name "brushless DC motor" strongly suggests a motor that runs on a DC power supply, Oriental Motor uses the term "brushless motor."



# 1 Types of Brushless Motors

Brushless motors combine permanent magnets, windings, magnetic pole sensors, and a drive circuit to perform the function of a motor. Since there are few structural limitations, many specialized motors with structures optimized for a specific purpose have been devised. We will explain the characteristics offered by the most typical structures.

## 1.1 Inner Rotor Type

The rotor is located inside the stator, and a permanent magnet is installed on the outer surface of the rotor. Due to a small rotor diameter and a low moment of inertia, it provides excellent acceleration and deceleration responsiveness. In addition, because the stator position is close to the motor surface, there is good heat radiation, allowing for a compact motor with high output power.

This is the typical configuration for brushless motors, and they are used for a wide variety of purposes. Oriental Motor's brushless motors are the inner rotor type.

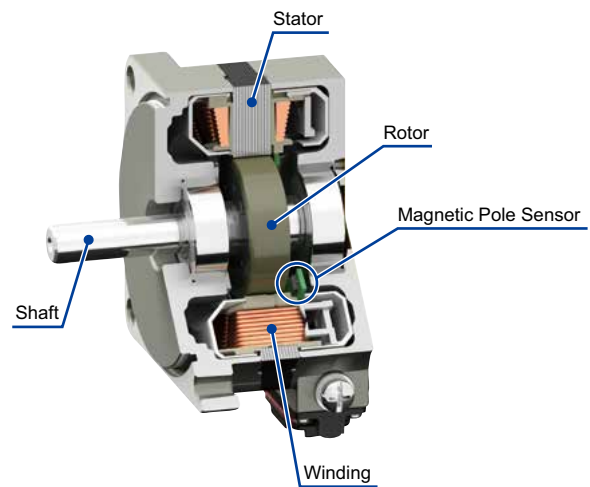


Fig. 1.1 Inner Rotor Type

## 1.2 Outer Rotor Type

With the rotor outside the stator and the permanent magnet inside the rotor, the locations of the stator and the permanent magnets are opposite of the inner rotor type. A cup-shaped rotor is not well-suited to nimble movements, because the moment of inertia is large and the acceleration and deceleration responsiveness are poor, but it provides excellent speed stability. This type is used in brushless DC fans that maintain a fixed rotation speed.

Because the rotor diameter is large, more magnets can be installed than with the inner rotor type, which allows for magnet multipolarity. This makes high output power possible at a compact size. However, because the windings are situated in the interior and heat radiation is poor, the windings heat up easily, which limits operating time. In drone motors that use an outer rotor, the rotor cup is equipped with ventilation holes, and the wind generated by the propellers keeps the windings cool.

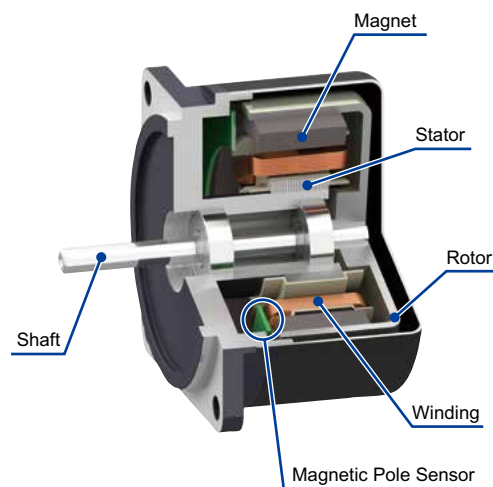


Fig. 1.2 Outer Rotor Type

### 1.3 Disk Rotor Type

The stator is formed by mounting the windings and magnetic pole sensors on the circuit board. Because the tabular permanent magnets are situated on the rotor surface so that they face the stator, this type of motor is thin. It is used to maintain a stable, fixed speed with a light load. There is no shaft, so an attachment for load connecting and disconnecting is installed to the rotor.

This type of motor is used in hard disk drives and disk drives for DVDs, Blu-ray discs, and other media.

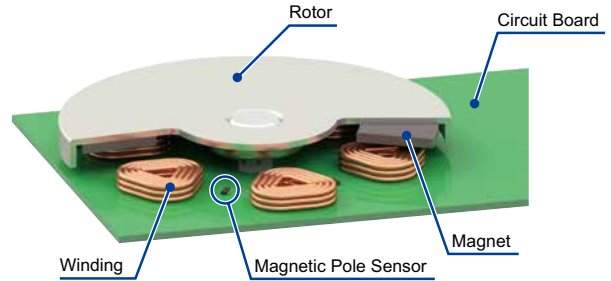


Fig. 1.3 Disk Rotor Type

## 2 Brushless Motor Structure and Principles

### 2.1 DC Motor Structure and Rotation Principles

Before explaining brushless motors, let us first introduce the structure and rotation principles for the DC motor, the precursor of the brushless motor. DC motor is an abbreviation for direct-current motor, and as the name implies, it is a motor that rotates by applying a direct-current voltage.

#### 2.1.1 DC Motor Structure

The general structure of a DC motor is shown in Fig. 2.1.

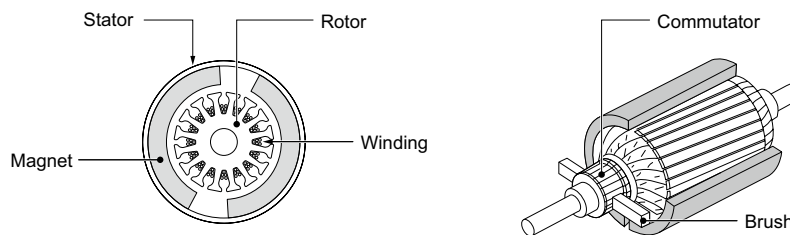


Fig. 2.1 DC Motor Structure

Permanent magnets are located within the stator, and situated in the center of these is a rotor containing windings. The rotor contains several windings, and both ends are connected to the commutator. Current flows through the windings via the commutator that is in contact with the brushes. The structure is such that rotation of the rotor switches the commutator segments coming into contact with brushes, and the windings through which the current flows switch over sequentially as well, continuing the rotation.

#### 2.1.2 DC Motor Rotation Principles

We will now explain the rotation principles for DC motors using Fleming's left-hand rule shown in Fig. 2.2 and the simplified model shown in Fig. 2.3.

Making a current flow through a conductor placed within a magnetic field causes the conductor to receive a force (electromagnetic force). According to Fleming's left-hand rule, the orientations of the magnetic field, current, and electromagnetic force are related orthogonally to one another.

The electromagnetic force generated in this condition is proportional to the magnetic field strength, the permeability, and the current value. Permeability  $\mu$  is a coefficient that represents the ease with which a substance can be magnetized, and the product of the magnetic field strength  $H$  and the permeability  $\mu$  is called the magnetic flux density  $B$ .

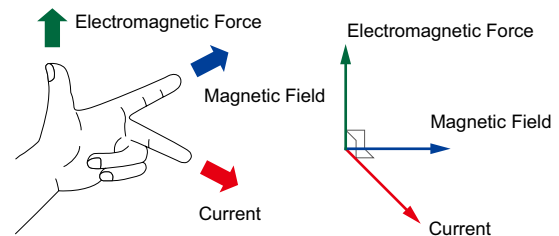


Fig. 2.2 Fleming's Left-Hand Rule

In the simplified model shown in Fig. 2.3, a pair of permanent magnets is arranged such that the north and south poles face each other. A single coil winding is located between the permanent magnets, and the structure allows for it to rotate freely around the dashed-dotted line.

Both ends of the coil are connected to the commutator, which is in contact with the brushes. The brushes are wired to a DC power supply, and current is supplied from the positive side, which passes through the coil and returns to the negative side.

For the explanation of the motor's rotation principles, let us assume that the orientation of the windings shown in Fig. 2.3 is the initial point (0°).

1. A current  $i$  flows through the brushes and commutator to the coil inside of the magnetic field.
2. According to Fleming's left-hand rule, the electromagnetic force  $F$  moves upward in the conductor on the north pole side and downward in the conductor on the south pole side, and the coil rotates clockwise.

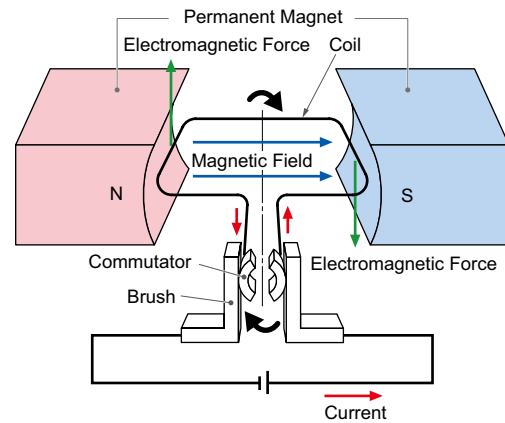


Fig. 2.3 Simplified Model of a DC Motor

3. When the coil rotates and approaches 90°, as shown in Fig. 2.4, the commutator and brushes are no longer in contact, and the current cannot flow. While the current may not be flowing, the coil rotates via the force of inertia.

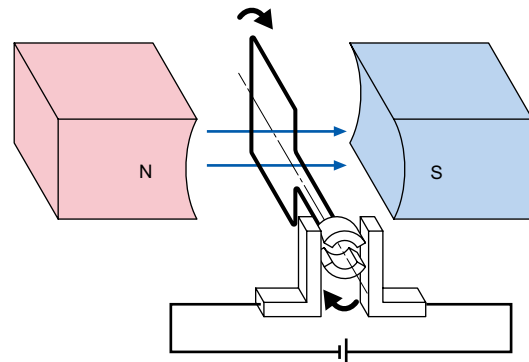


Fig. 2.4 At 90° Rotation

4. When the coil rotates via the force of inertia, the commutator and brushes make contact again, causing the current to flow and electromagnetic force to be generated. When it rotates to the 180° position shown in Fig. 2.5, it enters the same state that is shown in Fig. 2.3.

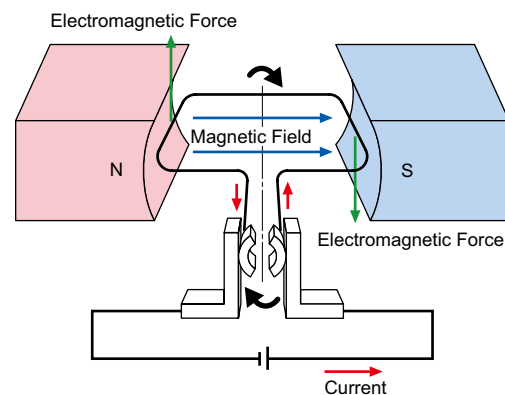


Fig. 2.5 At 180° Rotation

As stated above, the brushes and the commutator segments that are in contact with them switch places, which switches the direction of the current that flows through the coil, creating an electromagnetic force in the coil that moves in one direction. This allows the DC motor to continue rotating. The act of changing the direction of the current flowing through the coil is called commutation.



## Motor Torque

The electromagnetic force  $F$  generated in the conductor, the magnetic flux density  $B$ , and the current  $i$  are related as follows.

$$F = i B l \quad (2.1)$$

$l$ : The length of the conductor traversing the magnetic field

In addition, assuming the distance from the center of the rotation axis to the conductor is  $r$ , because the coil can be thought of as 2 conductors, the torque  $T$  that acts on the rotation axis is as follows.

$$T = 2 F r \quad (2.2)$$

Based on Formula (2.1) and Formula (2.2), the torque generated by the motor can be calculated via the following formula.

$$\begin{aligned} T &= 2 i B l r \\ &= Kt i \end{aligned} \quad (2.3)$$

$Kt$ : Torque constant

The torque constant  $Kt$  is a value intrinsic to the motor. From Formula (2.3), we can see that the torque of the DC motor and the current are proportional to one another.

### 2.1.3 DC Motor Characteristics

The DC motor speed - torque characteristics are shown in Fig. 2.6. The highest speed is achieved at the no-load state (in which no load is being applied to the shaft), and as the load torque increases, the rotation speed decreases. When the motor speed is zero (with the shaft in a fixed state), stall torque is generated.

This feature of sloping downward to the right is called the sloping characteristic. When a DC motor is actually used, this characteristic causes rotation to occur when the load torque and motor output torque are in equilibrium. For example, if the load torque  $T_L$  is applied at voltage  $V_1$ , the rotation speed will be  $N_1$ .

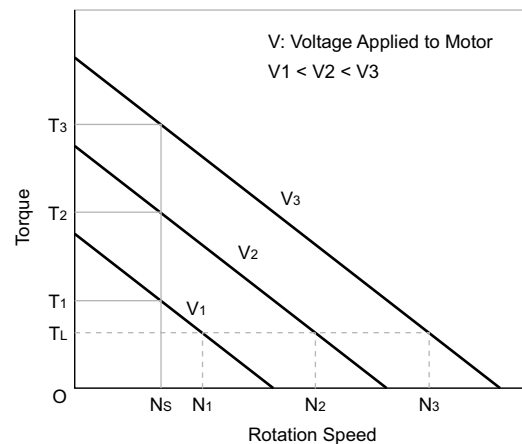


Fig. 2.6 Speed - Torque Characteristics

In addition, as shown in Formula (2.3), the generated torque is proportional to the current. For this reason, as the applied voltage increases from  $V_1 \rightarrow V_2 \rightarrow V_3$ , the motor current increases and the speed - torque characteristics change. If the applied voltage is changed from  $V_1$  to  $V_2$  and then to  $V_3$  at a constant load torque of  $T_L$ , the rotation speed will change from  $N_1$  to  $N_2$  and then to  $N_3$ . If the applied voltage is  $V_1$  and the load torque increases from  $T_1$  to  $T_2$  or  $T_3$ , the motor will stop, but if the applied voltage is changed from  $V_1$  to  $V_2$  or  $V_3$ , the motor generated torque changes to  $T_2$  or  $T_3$ , and for this reason the motor can operate at the constant rotation speed of  $N_s$ .

## 2.1.4 DC Motor Features

The features of DC motors with brushes are indicated below.

- **Advantages**

- There are 2 lead wires, and applying a DC voltage is enough to allow rotation.
- Inverting the polarity of the power supply inverts the rotation direction.
- Because permanent magnets are used, DC motors are compact, lightweight, and efficient.
- The starting torque is large and features excellent controllability.
- The torque is proportional to the voltage (current).
- Can be operated with dry cells and batteries.
- Low cost

- **Disadvantages**

- Brush abrasion makes for a short life span.
- Mechanical acoustic noise is generated.
- Electrical noise is generated.

Since DC motors can be operated simply by connecting a DC power supply, they are used for a number of applications. However, because the brushes and commutator sliding against one another causes brush abrasion, cleaning the abrasion powder, replacing the brushes, and other types of periodic maintenance are required. As the number of motors used increases, maintenance becomes increasingly difficult, which increased the demand for a maintenance-free motor with a long life span.

## 2.2 Brushless Motor Structure and Rotation Principles

Brushless motors maintain the excellent controllability of DC motors while eliminating their disadvantages, brushes and commutator, by replacing them with electronic components. Here, we will explain the differences in the structure and rotation principles of brushless motors.

### 2.2.1 Brushless Motor Structure

The rotor contains permanent magnets, and the stator contains windings, which means the structure reverses the locations of the stator and rotor in the DC motor shown in Fig. 2.1. With DC motors, causing a direct current to flow through the windings begins rotating the rotor, and the brushes and commutator segments in contact with them change positions, which changes the direction of the current flowing through the windings, thus continuing the rotation.

Since brushless motors create commutation without using brushes or commutator, they require magnetic pole sensors (hall elements, hall effect ICs, etc.) to detect the magnetic pole positions of the permanent magnets, as well as drivers for directing the current to flow through the windings according to the detected magnetic pole positions.

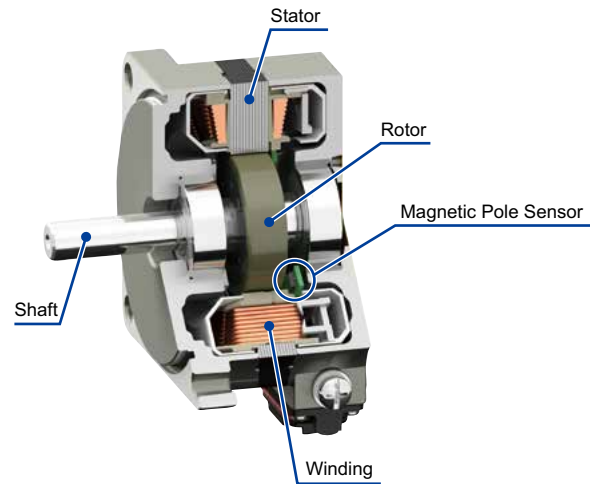


Fig. 2.7 Brushless Motor Structure

### 2.2.2 Brushless Motor Rotation Principles

To explain the rotation principles for brushless motors, we will use the simplified three-phase, 2-pole model shown in Fig. 2.8.

With rotor magnets, both the north pole and south pole have a magnetic pole angle of  $180^\circ$ . Magnetic pole sensors Ha, Hb, and Hc are spaced  $120^\circ$  apart, and they detect the north pole of the rotor magnets and output a signal.

With the stator, the phase-U coil, phase-V coil, and phase-W coil are spaced  $120^\circ$  apart and are offset from the magnetic pole sensors by  $60^\circ$ .

For each of the stator's phase windings, a south pole is generated in the inner diameter side of the stator when a current flows from the drive circuit to the motor. A north pole is generated in the inner diameter side of the stator when the current flows in the opposite direction. Fig. 2.8 shows the state when a current flows from phase-U to phase-V.

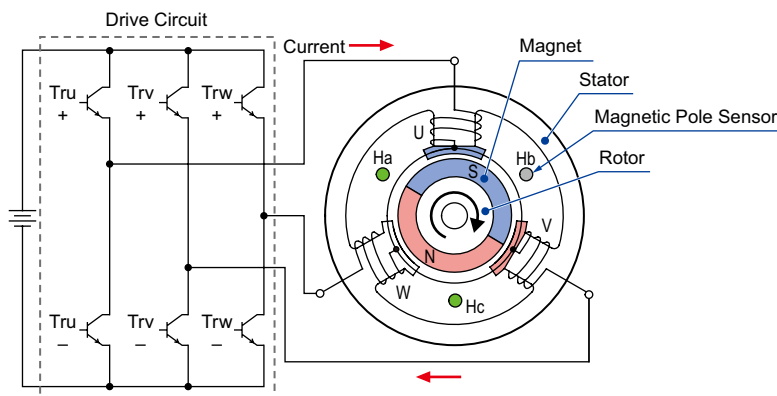


Fig. 2.8 Simplified Model of a Brushless Motor

For the explanation of the motor's rotation principles, let us use the rotation sequence shown in Fig. 2.9 and assume that the orientation of the rotor magnets shown in Fig. 2.8 is the initial point (0°).

1. In interval (a), magnetic pole sensors Ha and Hc detect the north pole and output a signal. In this case, if transistors Tru+ and Trv- are turned ON, a current flows from the phase-U coil to the phase-V coil in the stator. At this time, the phase-V is magnetized in the north pole (excitation), and attracts the south pole and repels the north pole in the rotor magnets. The phase-U is magnetized in the south pole (excitation) and repels the south pole in the rotor magnets. This causes the rotor to rotate clockwise.
2. In interval (b), which is past 60°, only magnetic pole sensor Ha detects the north pole and outputs a signal. In this case, if transistors Tru+ and Trw- are turned ON, a current flows from the phase-U coil to the phase-W coil in the stator. The phase-U maintains excitation, and attracts the north pole and repels the south pole in the rotor magnets. The phase-W is excited at the north pole and repels the north pole in the rotor magnets. This causes the rotor to rotate clockwise.
3. For each 60° of rotation, the combination of ON and OFF states for magnetic pole sensors Ha, Hb, and Hc changes. For a single rotation of the motor, there are 6 different magnetic pole sensor output combinations, represented by (a) through (f). Through the sequential switching of a determined set of excited phases for each pattern, a rotating magnetic field is continuously generated.

In addition, by changing the way the current flows through the coil for each of the output combinations for magnetic pole sensors Ha, Hb, and Hc, the motor rotation direction can be reversed.

For example, if transistors Trv+ and Tru- are turned ON when only magnetic pole sensor Ha detects a north pole and outputs a signal at interval 2. (b) noted above, a current flows from the phase-V coil to the phase-U coil in the stator. At this time, the phase-U is excited at the north pole, and attracts the south pole and repels the north pole in the rotor magnets. The phase-V is excited at the south pole and repels the south pole in the rotor magnets. This causes the rotor to rotate counter-clockwise.

In summary, brushless motors rotate by causing current to flow through the phase coils according to the magnetic pole sensor output signals.

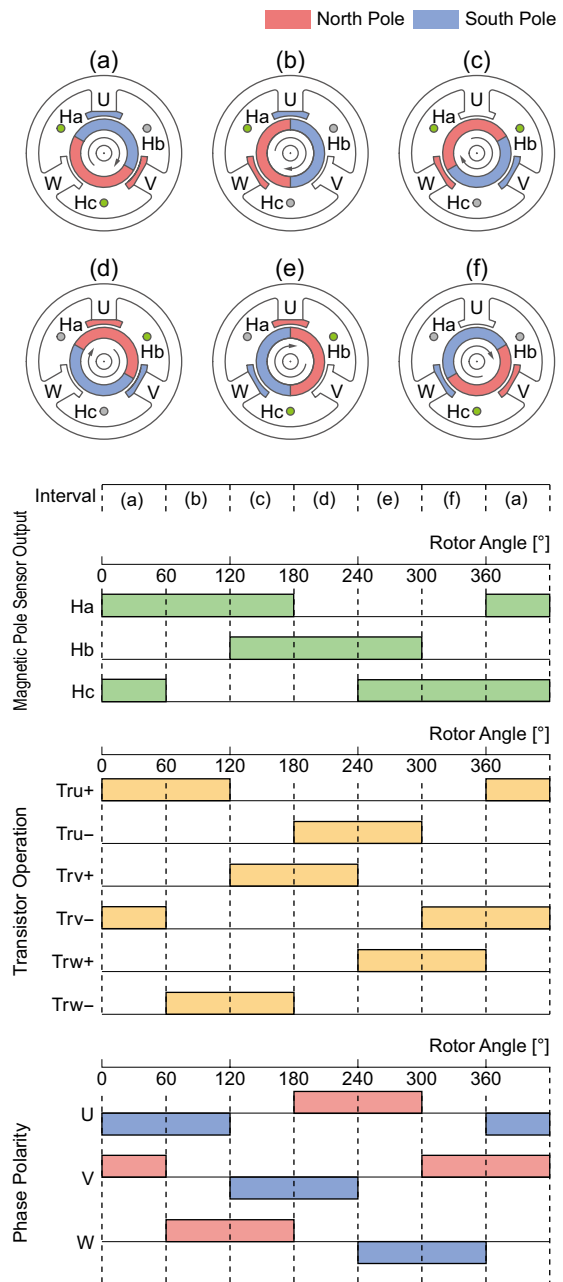


Fig. 2.9 Rotation Sequence



## Brushless Motor Currents

Direct voltage is applied to the drive circuits of brushless motors, but an alternating current flows through the motor. For this reason, brushless motors are sometimes called AC synchronous motors.

### 2.2.3 Brushless Motor Characteristics

As explained in “2.2.1 Brushless Motor Structure,” the stator and rotor positions in brushless motors are the opposite of their positions in DC motors. For this reason, the fundamental speed - torque characteristics for brushless motors exhibit the same sloping characteristics as DC motors, as shown in Fig. 2.10, and the motor rotates at a rotation speed that matches the load torque.

If the speed slows down, the torque generated by the motor increases, and a current proportional to the torque flows. If a large current flows, the magnetic force of the permanent magnet in the motor may decrease (demagnetization) and the windings may overheat and experience burnout. In addition, the output element and converter on the drive circuit must be able to handle large currents, which causes the drive circuit to be large and expensive.

If the speed increases, the torque generated by the motor decreases, and the load torque required for driving decreases, making it unsuitable for use. Operating it at a higher speed increases the noise emitted by the gearhead combined with the motor, and it also causes insufficient gearhead lubrication, which affects the life span.

For the above reasons, with brushless motors, the drive circuit limits the maximum current that flows through the motor and the maximum rotation speed. Thus, the speed - torque characteristics printed in Oriental Motor’s product catalog is similar to Fig. 2.11.

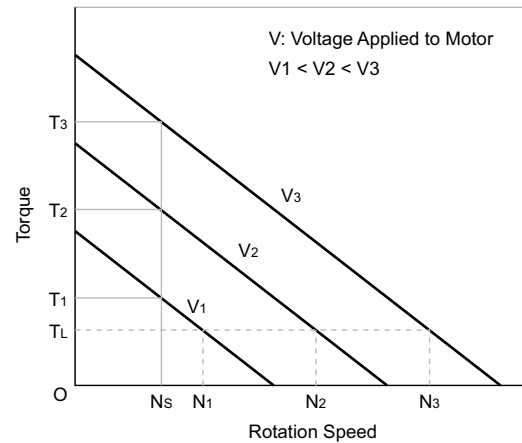


Fig. 2.10 Speed - Torque Characteristics

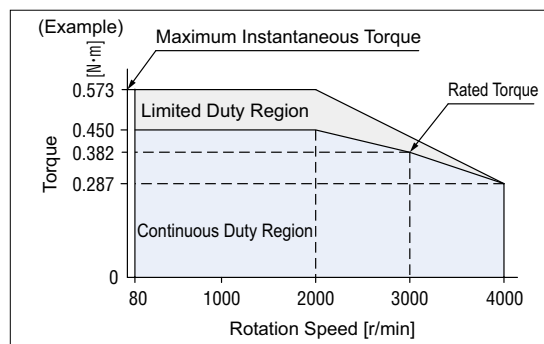


Fig. 2.11 Speed - Torque Characteristics

#### Limited Duty Region

The region consisting of rotation speed and torque combinations that can be used for short periods of time. Used to improve responsiveness during acceleration and deceleration.

#### Continuous Duty Region

The region consisting of rotation speed and torque combinations that can be used during continuous operation.



### Rotor Magnet Demagnetization

Permanent magnets are magnetized by applying a strong magnetic field to magnet materials. Conversely, causing excessive current to flow through a motor causes the stator to generate a diamagnetic field, which decreases the magnetic force of the rotor magnets. This is called demagnetization.

Oriental Motor’s motors are designed to prevent demagnetization at the current at which the maximum instantaneous torque is generated.

## 2.2.4 Brushless Motor Features

The features of brushless motors are indicated below.

### • Compared to DC Motors

- The speed - torque characteristics have the same sloping characteristics as DC motors and have excellent controllability.
- Because there are no brushes or commutators, there is no need to clean the abrasion powder, replace the brushes, or perform other periodic maintenance, giving them a long life span.
- Since there are no brushes or commutators, there is no electronic noise due to arcs. (Switching noise is generated.)
- No mechanical acoustic noise is generated.
- Magnetic pole sensors and drivers are needed for operation.
- Since the motor rotation speed is detected from the magnetic pole sensor output and feedback control is performed, there is high speed accuracy.
- Because there is feedback control, abnormal behavior can be detected during operation.

### • Compared to Inverter Control Motors and AC Speed Control Motors

- Since the torque is flat from low speed to high speed, the speed ratio is large for all practical purposes.
- If compared at the same output power, the motor is compact and high efficiency.
- Can be used with a DC power supply.
- Because the motor rotation speed is detected from the magnetic pole sensor output and feedback control is performed, there is high speed accuracy.
- Since there is feedback control, malfunction can be detected during operation.

Because DC motors are inexpensive, they are used for various applications where required life span is relatively short. However, for general industrial use, not only are there problems with the life span and maintainability, but there is also a need for a high level of reliability in terms of speed accuracy during operation, malfunction detection, and so on, which has led to the increasing popularity of brushless motors. In addition, because the motors are compact, have high output power, and are highly efficient, they are used in devices that need to be compact and lightweight, as well as for battery-powered devices.

## 2.3 Main Components of Brushless Motors

Here, we will explain the main components that brushless motors are constructed from.

### 2.3.1 Components for Detecting Magnetic Pole

#### a. Hall Element

A hall element is a magnetic detection element that utilizes the hall effect to detect the magnetic fields of the rotor magnets and output signals.

The state of a hall element that is affected by the magnetic field from a north pole is shown in Fig. 2.12.

If a current flows from the upper part to the lower part of the element and it is affected by a magnetic field from the north pole in the direction indicated by the arrow, the distribution of the electric charges inside the element is unbalanced by the electromagnetic force. As a result, an electromotive force that crosses both the current and the magnetic field at right angles is generated.

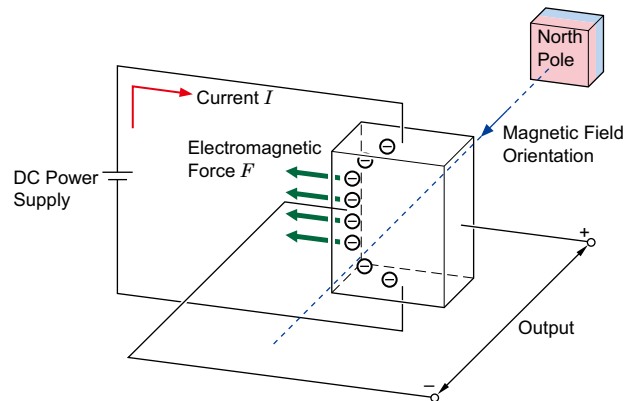


Fig. 2.12 Hall Element Detection Principles

The hall element output signal is a weak analog voltage of several 100 mV. If north and south poles continuously alternate as with a motor, then, as shown in Fig. 2.14, there will be a constant output in the areas where the magnetic field is stabilized, and it will change gently in the areas where the magnetic poles switch.

Since the signals are weak, they are easily influenced by noise where the signal lines are long and in environments where there is a lot of electronic noise. A hall effect IC addresses the noise by integrating a circuit that shapes and amplifies the hall element output signals before outputting them.



#### Discovery of the Hall Effect

The hall effect was discovered in 1879 by American physicist Edwin Herbert Hall.

Applying a magnetic field perpendicularly to an object with electricity flowing through it generates an electromotive force perpendicular to both the current and the magnetic field. Hall elements are semiconductors that utilize this principle. The electromotive force continuously changes depending on the strength of the magnetic field.

## b. Hall Effect IC

A hall effect IC is a magnetic sensor that integrates the hall element and the amplifying and shaping circuit into a single package (IC). Fig. 2.13 shows the internal structure of a hall effect IC, and Fig. 2.14 shows the relationship between the hall effect IC output signals and the hall element output signals in relation to the magnetic fields of the rotor magnets.

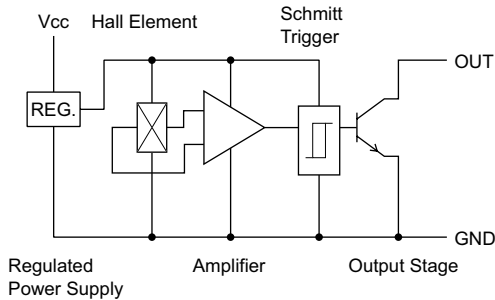


Fig. 2.13 Hall Effect IC Block Diagram

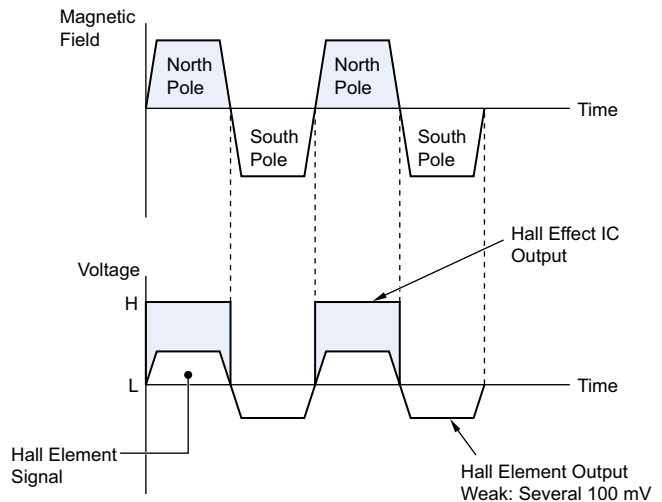


Fig. 2.14 Hall Effect IC Output Signal

An amplifier is used to amplify the weak output signal resulting from a hall element detecting a magnetic field, and it is shaped using a Schmitt trigger and output. If the magnetic field strength of the rotor magnets exceeds the hall effect IC threshold, a signal is output, and if it is lower than the threshold, the signal stops. A hall effect IC is resistant to noise compared to the hall element output voltage, and it is simple to use.

## c. Encoder

Hall effect ICs detect the magnetic poles of the rotor magnets and perform output, but the encoder converts the light that passes through the encoder disk slit into an electric signal via a light-receiving component, then amplifies and shapes it before outputting the signal.

As shown in Fig. 2.15, an encoder is equipped with small slits used for position and speed detection (phase A, phase B), as well as slits for detecting the magnetic pole position. The light-receiving components for detecting the position and speed are arranged such that the signal phase difference as an electrical angle is  $90^\circ$  in relation to the encoder disk slits. Thus, it can accurately detect not only the motor rotation speed, but also the rotation amount and rotation direction.

In addition, the 3 slits for detecting magnetic pole positions and the light-receiving components are arranged such that the signal phase difference as an electrical angle is  $120^\circ$ , and the encoder and rotor are separate parts, so the timing of the switching for the rotor magnetic pole position and the magnetic pole detection signal do not match. To make this timing match, it is necessary to adjust the position of the slits for detecting magnetic pole position when installing the encoder.

Oriental Motor has products equipped with encoders with magnetic pole detection signals. Since the rotation speed and rotation amount can be accurately detected via the phase A and phase B signals, stable speed control at low speeds and position control are possible. (For details, refer to “5.1.3 Speed Detection Accuracy.”)

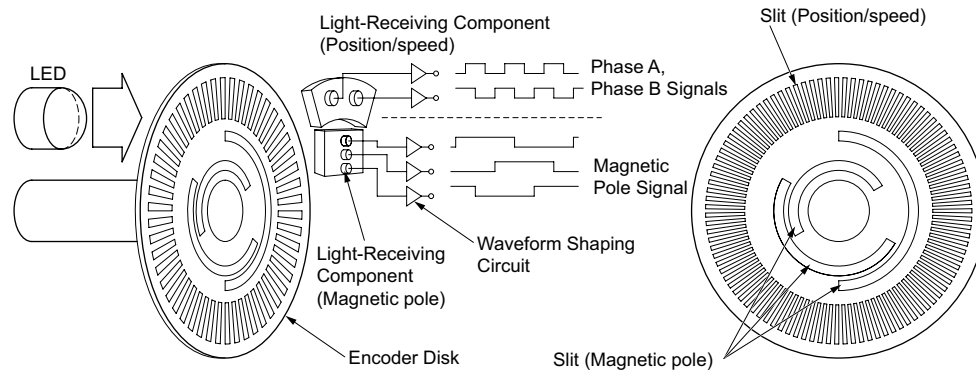


Fig. 2.15 Encoder Structure

### 2.3.2 Components That Generate Magnetic Fields

With induction motors, torque is generated via the current induced in the rotor and the rotating magnetic field in the stator, but with synchronous motors such as brushless motors, torque is generated via magnetic fields from permanent magnets and the rotating magnetic field in the stator. Here, we will explain the permanent magnets in the main components that are crucial for supporting the compact size, high output power, and high efficiency brushless motors are known for.

#### a. Ferrite Sintered Magnets

Invented by a Japanese person in 1930. Because ferric oxide is the principal component, it is cost-effective. In addition, because no surface treatment is required, it has good cost performance, and it is still the most commonly produced and used magnet worldwide.

- Maximum energy product (BH) max. 8.0 to 43.8 kJ/m<sup>3</sup> [1.0 to 5.5 MGOe]

#### b. Rare Earth Sintered Magnets

There are samarium-cobalt (SmCo) varieties and neodymium (NdFeB) varieties, with neodymium magnets having the highest performance, making them essential for compact, energy-saving motors. However, because few countries produce the rare-earth elements used to make them, few are produced, and they are expensive.

- Maximum energy product (BH) max. 199 to 414 kJ/m<sup>3</sup> [25 to 52 MGOe]

#### c. Bonded Magnets

These magnets are molded and manufactured by mixing fine magnetic powder from ferrite and rare-earth magnets with resin and other binders. Since they can freely assume many shapes, they have excellent workability in assembly and jointing work, but because they contain non-magnetic components, their magnetic properties are half or less than those of sintered magnets.

- Maximum energy product (BH) max.
  - Neodymium-type 63 to 159 kJ/m<sup>3</sup> [8 to 20 MGOe]
  - Ferritic 5.6 to 17.5 kJ/m<sup>3</sup> [0.7 to 2.2 MGOe]



## History of the Invention of Permanent Magnets

The development of brushless motors is closely connected to that of permanent magnets. The invention of high-performance magnets allowed for motors to be made increasingly compact, high-output power, and high-efficiency. Below is a chronological list of appearances and evolutions of permanent magnets in modern times.

Year	Main Events Related to Permanent Magnets and Magnetism
1917	"KS steel" is invented by Dr. Honda (Japan)
1919	"The Barkhausen effect" is discovered (Germany)
1930	"The magnetic domain structure and the principle of magnetic domain" are explained using the Bitter technique
1930	The world's first "ferrite magnet and OP magnet" are invented by Dr. Kato and Dr. Takei (Japan)
1932	"MK steel" is invented by Dr. Mishima (Japan)
1934	"NKS steel" is invented by Dr. Honda (Japan)
1936	"Platinum cobalt (Pt-Co) magnets" are developed (Germany)
1938	"Alnico magnets" are developed (U.S.A.)
1952	"Barium ferrite magnets" are developed (The Netherlands)
1960	"Manganese-aluminum (Mn-Al) magnets" are invented (The Netherlands)
1961	"Strontium ferrite magnets" are developed (U.S.A.)
1966	"Samarium-cobalt (SmCo <sub>5</sub> ) powder magnets" are developed (U.S.A.)
1969	"Samarium-cobalt (SmCo <sub>5</sub> ) sintered magnets" are developed (U.S.A.)
1970	"Manganese-aluminum-carbon (Mn-Al-C) magnets" are invented and industrialized (Japan)
1971	"Iron-chromium-cobalt (Fe-Cr-Co) magnets" are invented by Dr. Kaneko (Japan)
1972 - 1974	"Samarium-cobalt (SmCo <sub>5</sub> ) sintered magnets and bonded magnets" are industrialized (Japan)
1976	"Samarium-cobalt (Sm <sub>2</sub> Co <sub>17</sub> -type) sintered magnets" are made available for practical use (Japan)
1983	"Neodymium (Nd-Fe-B) magnets" are invented using the fast quenching method (U.S.A.)
1983	"Neodymium (Nd-Fe-B) sintered magnets" are invented (Japan)

\* From the NeoMag Co., Ltd. website

# 3 Brushless Motor Drive System

Brushless motors rotate by causing a current to flow through the motor windings toward the rotor magnetic poles with the appropriate timing. There is a close relationship between the drive system (the way the current flows) and the motor characteristics, and various methods have been used to improve the controllability and characteristics of motors. Here, we will explain a typical drive system and current control method.

## 3.1 Motor Drive System

### 3.1.1 Square Wave Drive System (120° conduction mode)

There are many types of brushless motor drive systems, and the 120° conduction mode's square wave drive is one common example. As shown in Fig. 3.1, this method involves switching the excitation state according to the combinations of hall effect IC output signals. While speed ripples occur during low-speed operation, high output power can be achieved with a simple circuit, therefore it is widely used to control brushless motors for office automation equipment and power devices.

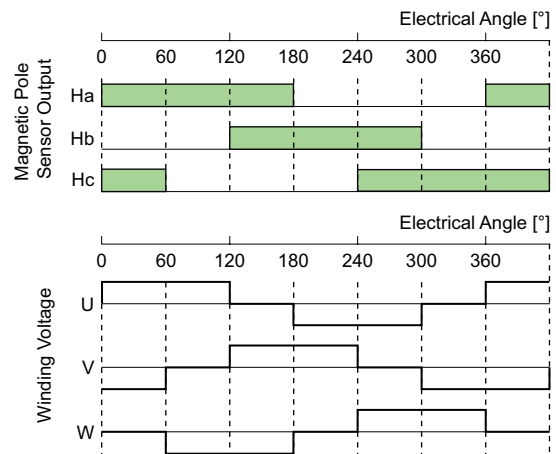


Fig. 3.1 Square Wave Drive Excitation Patterns

### 3.1.2 Sine Wave Drive System

A sine wave drive system is a drive system that exerts fine control over the applied voltage, as shown in Fig. 3.2, to make the motor current sinusoidal. This drive system has few torque ripples and allows for stable rotation. In addition, it also reduces the noise generated from driving the motor.

However, to perform sine wave driving, it is necessary to accurately detect the rotor magnetic pole positions. Traditionally, a high-resolution encoder was required, but this had the disadvantage of increasing the overall length and cost of the motor.

In recent years, rather than use an encoder:

- Software has been used to process the hall effect IC signals.
- Detection has been performed using motor inductance and back EMF.

Thus, it is now possible to detect the magnetic pole positions using various other methods and perform sine wave driving.

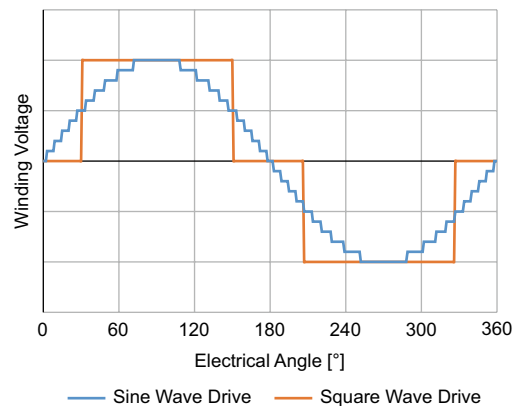


Fig. 3.2 Applied Voltage for Sine Wave Drive and Square Wave Drive (Single-phase)

### 3.1.3 Current Waveforms for Each Type of Drive System

Actual current waveforms are shown in Fig. 3.3. A square wave drive has distortion with respect to applied voltage waveform, and it is actually closer to sine waves in form than square waves. A sine wave drive has a waveform similar to that of applied voltage waveforms.

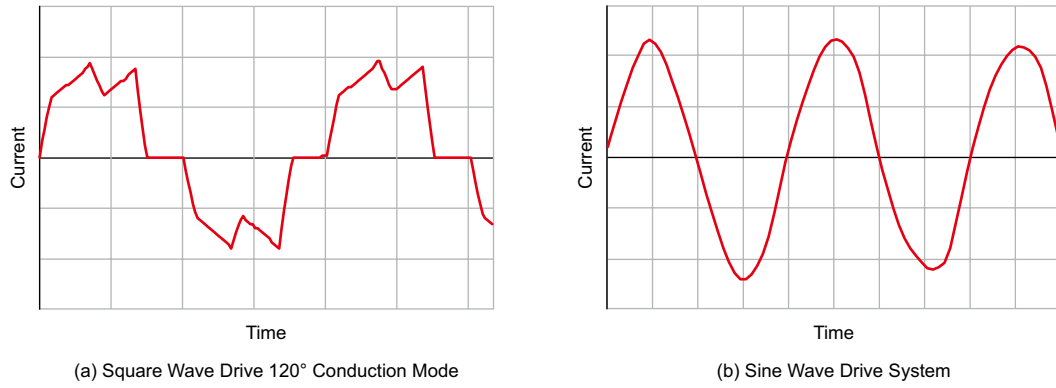


Fig. 3.3 Current Waveform

## 3.2 Drive Systems and Motor Torque

A sine wave drive system has smaller torque ripples than a square wave drive system and allows for smoother operation. Let us consider the reasons for this using the principles of motor torque generation. The ideal driving method for a motor is one that operates such that the magnetic flux and coil current are always orthogonal to one another in accordance with the Fleming's left-hand rule, as shown in Fig. 2.2. This driving method applies to all motor types. In DC motors, this is done through mechanical commutation. To explain the principles of torque generation for brushless motors, we will use a simplified three-phase, 2-pole model as shown in Fig. 3.4.

Rotors contain a rotational axis in the center between the north and south poles. In the stator that surrounds the rotor magnets, phase-U, phase-V, and phase-W coil windings are offset 120° from one another.

U+, V+, and W+ are connected to the drive circuit, and Uc, Vc, and Wc are connected at one point (common). Here, we will designate the direction that flows from the drive circuit to the common as plus and the direction that flows from the common to the drive circuit as minus.

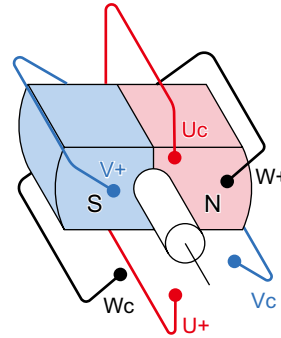


Fig. 3.4 Simplified Three-Phase, 2-Pole Model

Let us take a detailed look at the coils of a particular phase. As you can see from the state of the coil and rotor magnets in Fig. 3.5, the rotor and stator positions are the opposite of what they would be in a DC motor. If a current flows at this point, as shown in Fig. 3.5, a downward electromagnetic force will be generated on the south pole side, and an upward electromagnetic force will be generated on the north pole side, as determined by the Fleming's left-hand rule. However, because the coils in a brushless motor are fixed, a reactive force acting on the rotor magnets turns the rotor clockwise.

The electromagnetic force  $F$  [N] that acts on the windings in the state shown in Fig. 3.5 is calculated using the below formula that was explained in the DC motor rotation principles section.

$$F = i B l \quad (3.1)$$

$i$  : Current [A]

$B$  : Magnetic flux density [T]

$l$  : The length of the conductor traversing the magnetic field [m]

However, if the rotor rotates and assumes the state shown in Fig. 3.6, the electromagnetic force  $F$  that acts on the conductor is generated in the direction that extends the coil toward the outer side, so no force (torque) is generated toward the rotor magnets in the rotation direction.

In other words, with respect to the conductor, the direction of the magnetic flux density  $B$  that acts as a torque is orthogonal to the rotation axis and changes according to the rotation angle of the rotor magnets.

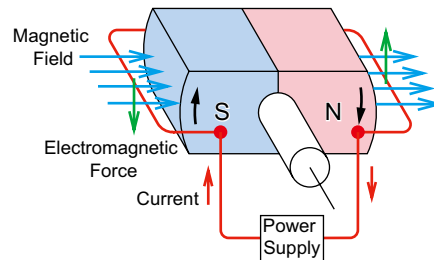


Fig. 3.5 Generated Torque at the Maximum

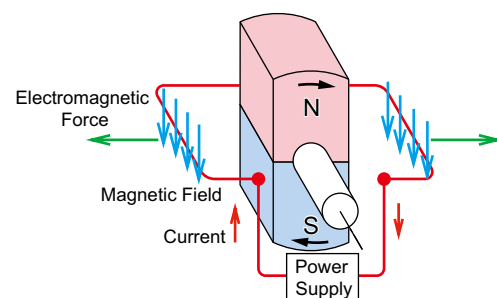


Fig. 3.6 No Torque Generated

When the rotor has rotated, it is assumed that the magnetic flux density that acts as torque (hereinafter referred to as the magnetic flux density) on the coils of the phase-U, phase-V, and phase-W, which are offset from one another by 120°, changes into a sinusoidal form.

When it has rotated clockwise with the rotor angle shown in Fig. 3.4 at 0° and the maximum magnetic flux density as  $B_0$ , the relationship between the rotor angle and the magnetic flux densities for the phases, represented as  $B_u$ ,  $B_v$ , and  $B_w$ , are represented by Formula (3.2).

$$\left. \begin{aligned} B_u &= B_0 \sin\theta_r \\ B_v &= B_0 \sin\left(\theta_r - \frac{2}{3}\pi\right) \\ B_w &= B_0 \sin\left(\theta_r - \frac{4}{3}\pi\right) \end{aligned} \right\} \quad (3.2)$$

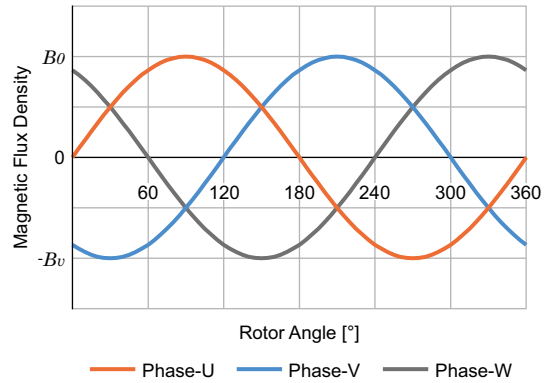


Fig. 3.7 Magnetic Flux Density

### 3.2.1 For a Square Wave Drive System

To explain the motor torque when using a square wave drive, we will use a simplified three-phase, 2-pole model as shown in Fig. 3.4.

#### a. Driving Current

For brushless motors with a square wave drive system, as explained in “2.2.2 Brushless Motor Rotation Principles,” current flows to the coils in phase-U, phase-V, and phase-W according to the excitation patterns from the rotor angles detected by the magnetic pole sensor.

If there is a clockwise rotation with the rotor angle shown in Fig. 3.4 at 0° and the motor current as  $i_m$ , the relationship between the rotor angle and the phase currents for each of the phases is as indicated in Fig. 3.8.

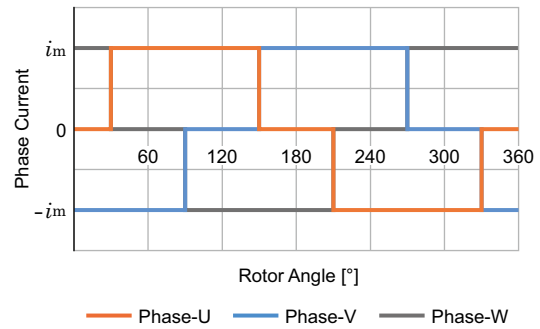


Fig. 3.8 Square Wave Drive Current Waveform

At this point, when the rotor angle is between 30° and 150°, the current flowing through the phase-U is  $i_m$ , and between 210° and 330°, it is  $-i_m$ . The currents for the phase-V and phase-W experience a phase delay of 120° and 240°, respectively, with respect to the phase-U current.

#### b. Motor Torque

The torque  $T$  generated by each of the phase coils is calculated using the electromagnetic force  $F$  and the distance  $r$  from the center of the rotor rotation to the conductor.

$$T = 2 F r \quad (3.3)$$

$$T = 2 i B l r \quad (3.4)$$

Thus, the motor torque is the sum of the torques generated by the coils in each of the phases, and it is represented by the following formula.

$$T = 2 ( i_u B_u + i_v B_v + i_w B_w ) l r \quad (3.5)$$

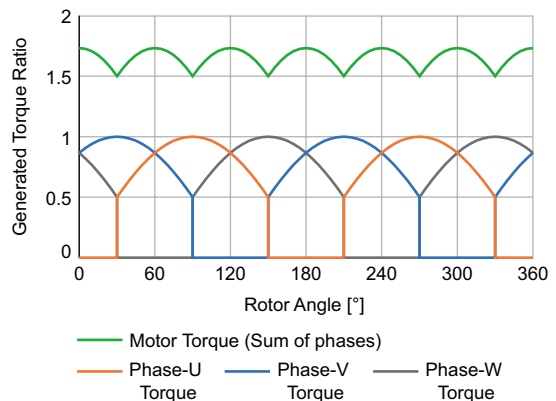


Fig. 3.9 Square Wave Drive Torque Waveform

If  $r$ ,  $l$ ,  $i_m$ , and  $B_0$  are set to 1, and the torque for each phase is calculated from the current and magnetic flux density for each rotor angle using Formula (3.2), Fig. 3.8, and Formula (3.5), the result is the torque waveforms shown in Fig. 3.9. Because 6 torque ripples are generated for each rotation, speed ripples are generated during low speed rotation.

### 3.2.2 For a Sine Wave Drive System

To explain the motor torque when using a sine wave drive, we will use a simplified three-phase, 2-pole model as shown in Fig. 3.4.

#### a. Driving Current

When the rotor has rotated clockwise, a sinusoidal current with a phase difference of  $120^\circ$ , as shown in Fig. 3.10, flows to the coils of the phase-U, phase-V, and phase-W, which are offset  $120^\circ$  from one another. In Fig. 3.4, if there is a clockwise rotation with the rotor angle at  $0^\circ$  and the maximum value of the current at  $i_m$ , the currents for each phase, denoted as  $i_u$ ,  $i_v$ , and  $i_w$ , are represented by Formula (3.6).

$$\left. \begin{aligned} i_u &= i_m \sin \theta_r \\ i_v &= i_m \sin \left( \theta_r - \frac{2}{3} \pi \right) \\ i_w &= i_m \sin \left( \theta_r - \frac{4}{3} \pi \right) \end{aligned} \right\} \quad (3.6)$$

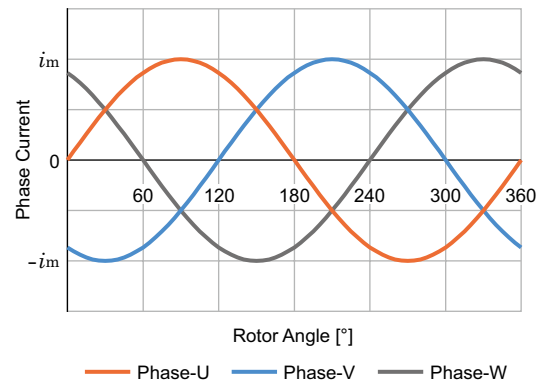


Fig. 3.10 Sine Wave Drive Current Waveform

#### b. Motor Torque

Just as with the square wave drive, the motor torque is the sum of the torques generated by the coils in each of the phases, and it is calculated using Formula (3.5).

In addition, Formula (3.5) can be simplified using Formula (3.2) and Formula (3.6) as shown below.

$$T = 3 r i_m B_0 l \quad (3.7)$$

If  $r$ ,  $l$ ,  $i_m$ , and  $B_0$  in Formula (3.7) are set to 1, and the sum of products for the current and magnetic flux density for the phases for each rotor angle is calculated, the result is the torque waveforms shown in Fig. 3.11. In Formula (3.7), the term for the rotor angle  $\theta$  disappears, and the motor torque in Fig. 3.11 is constant. In other words, with a sine wave drive, there are no torque ripples in any rotation, and smooth operation is possible during low speed rotation.

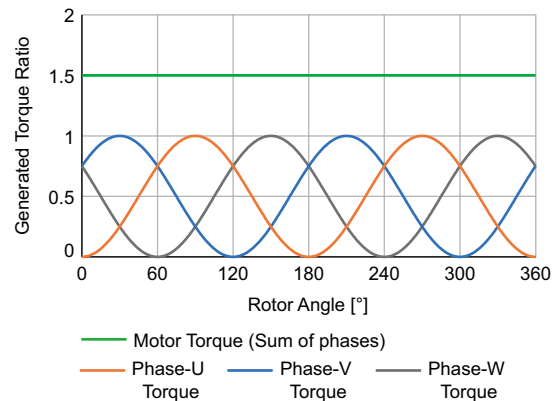


Fig. 3.11 Sine Wave Drive Torque Waveform

### 3.3 Current Control Method

Brushless motors have different methods of controlling current flow depending on the drive system. In addition, to control the rotation speed and generated torque, it is necessary to control the amount of the motor current. Here, we will explain a method for controlling the motor current.

An electrical control system called PWM (Pulse Width Modulation) is used as a control method for the voltage that is applied to the motor windings. PWM control is a method of controlling the output voltage by repeatedly turning the switching element in the circuit ON and OFF and creating a pulse-shaped voltage.

Fig. 3.12 shows a PWM control circuit model for a DC motor. Fig. 3.13 shows the voltage waveform and current waveform when the pulse width changes (modulation) during the ON phase. Modulating the pulse width and changing the duty ratio for the ON/OFF switching element controls the average voltage.

At this point, the inductance causes the current to lag behind the increased voltage, and when the application of voltage is removed, it gradually decreases.

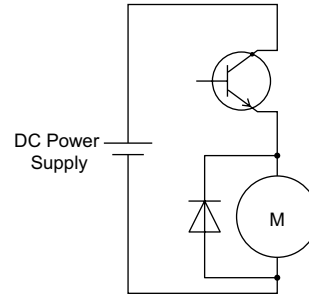


Fig. 3.12 PWM Circuit

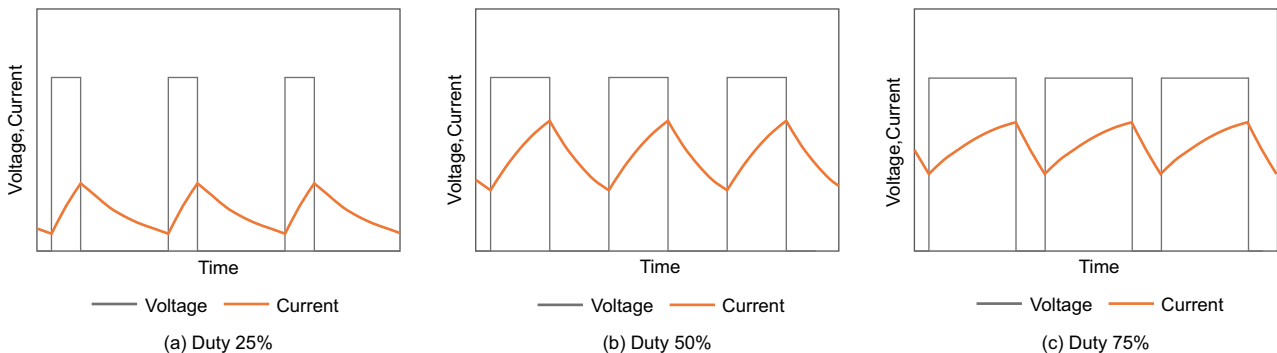


Fig. 3.13 Voltage Duty and Current Waveform

#### 3.3.1 Modulation Method

Let us explain the modulation method for PWM control, which was explained in Fig. 3.13. The PWM control duty ratio is decided by comparing the standard triangular wave signal and reference voltage and turning the switching element ON if that the triangular wave signal voltage is lower than the reference voltage, or OFF if it is higher. In order to increase the motor current, the reference voltage needs to be increased. This means that the switching element duty ratio gets larger, and because the average voltage increases, the motor current increases. If the reference voltage is lowered, the switching element duty ratio gets smaller, and because the average voltage decreases, the motor current decreases.

Brushless motors with a square wave drive system adjust the motor current using PWM control for the switching element that excites the motor windings, and they control the rotation speed and generated torque.

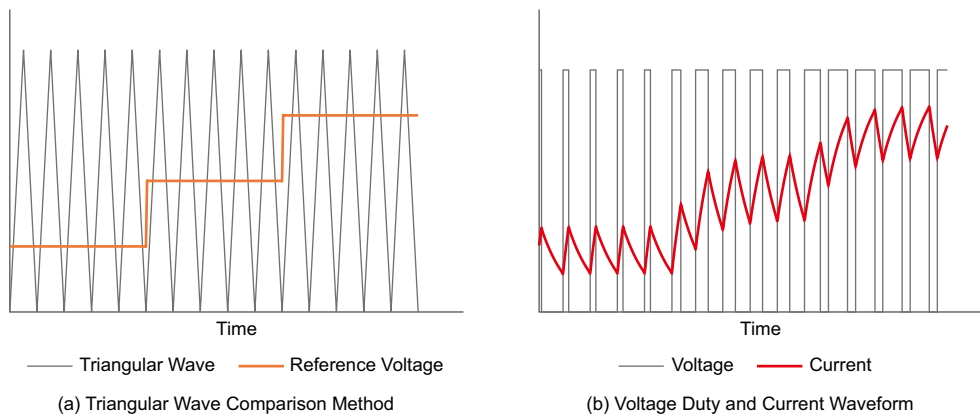


Fig. 3.14 Reference Voltage and Current

### 3.3.2 Sine Wave Drive System Modulation Method

Let us explain the modulation method for a sine wave drive system, which was explained in Fig. 3.10. If the reference voltage is made into a sinusoidal shape, the switching element duty ratio continuously modulates and a sinusoidal current can flow. In other words, with PWM control, the reference voltage waveform and the current waveform assume the same form. (The reference voltage for the waveform one wishes to output is called the modulating signal.) Brushless motors with a sine wave drive system perform PWM control just like with a square wave drive system, but the reference voltage creation method is different.

The sine wave motor current from Formula (3.6) is a function of the current maximum value  $i_m$  and the rotor angle  $\theta$ . That is, by creating a modulating signal from the rotor angle information and the current command value, the current that flows to the motor windings is adjusted and the rotation speed and generated torque are controlled.

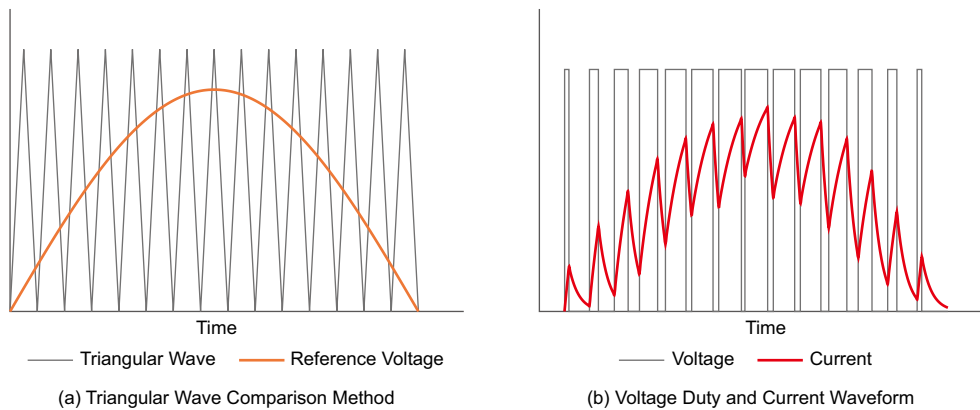


Fig. 3.15 Sine Wave PWM Drive

Thus, to perform sine wave driving in brushless motors, it is necessary to precisely detect the rotor magnet angles.



# 4 Brushless Motor Control Principles

Brushless motors can be operated by combining them with drive circuits. To operate the motor at the commanded rotation speed, a system is needed to control the speed. Here, we will explain the drive circuit configuration and methods for controlling the speed in brushless motors.

## 4.1 Basic Drive Circuit Configuration and Roles

The basic configuration for a drive circuit for a brushless motor is shown within the broken lines in Fig. 4.1. If we look at the configuration in terms of function, it can be divided into 6 blocks.

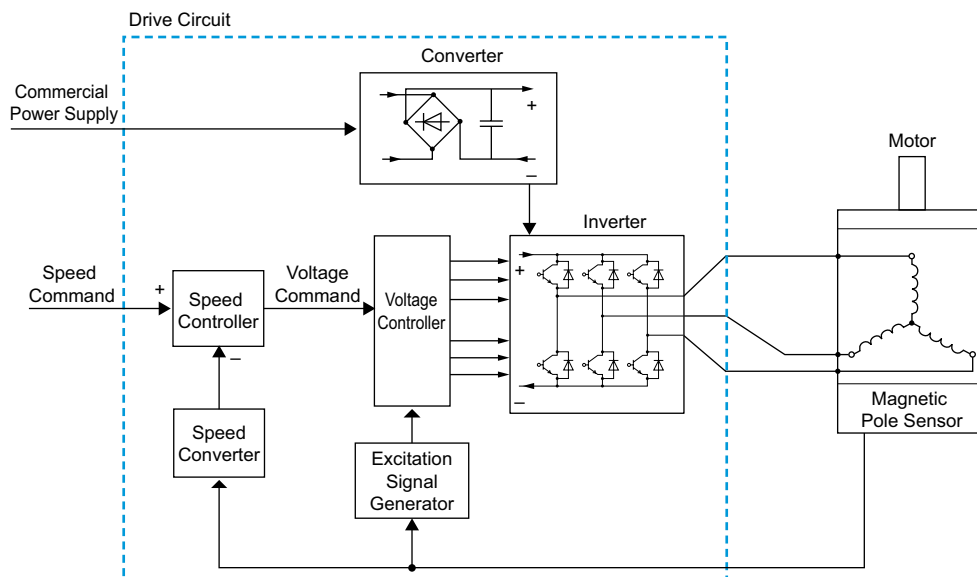


Fig. 4.1 Basic Drive Circuit Configuration

### 4.1.1 Converter

The converter commutates the AC voltage of the commercial power supply and smooths it out with a capacitor to convert it into DC voltage. DC voltage is supplied to the inverter and used to drive the motor.

There is no converter in brushless motors with DC power input. DC voltage is supplied directly to the inverter from the DC power supply.

### 4.1.2 Speed Controller

The speed controller compares the speed command and the motor speed (feedback speed) that is output from the speed converter and issues a voltage command to ensure that the motor rotation speed follows the speed command.

A control system that utilizes speed commands and speed feedback information is called a speed loop.

### 4.1.3 Speed Converter

A speed converter converts the hall effect IC output frequency into the speed feedback and outputs it to the speed controller.

There are 3 hall effect ICs in a three-phase brushless motor, and 3 pulse signals are output from each pair of north and south magnetic poles. By detecting the up edge and down edge of the pulse signals, 6 signals can be obtained.

### 4.1.4 Excitation Signal Generator

The excitation signal generator indicates to the voltage controller which element among the 6 switching elements in the inverter the current is flowing through.

As shown in Fig. 4.1, the rotor magnetic pole position is detected through combinations of output signals from the hall effect ICs (Ha, Hb, and Hc) arranged within the motor. The excitation signal generator indicates to the voltage controller the switching elements connected to the windings that generate torque based on the rotation direction commands.

### 4.1.5 Voltage Controller

The voltage controller outputs a signal that applies the voltage commanded by the speed controller to the inverter switching elements indicated by the excitation signal generator.

### 4.1.6 Inverter

The inverter performs PWM control for the motor windings according to the commands from the voltage controller.



#### How to Calculate the Rotation Speed

If the number of poles in the rotor is  $n$  and the period of the pulse signals is  $\Delta t$ , the motor rotation speed  $N$  is calculated according to Formula (4.1).

$$N = \frac{60}{3n \Delta t} \quad (4.1)$$

$N$  : Motor rotation speed [r/min]

$\Delta t$  : Pulse period [s]

## 4.2 Speed Control Methods

To explain the methods for controlling the speed of a brushless motor, we will use the process beginning with the motor in a stopped state up until it achieves the commanded speed as an example.

1. Input a speed command to the speed controller.
2. The speed controller compares the speed command and the feedback speed.
3. Because the feedback speed is lower than the speed command, the speed controller outputs a high voltage command to the voltage controller.
4. The inverter is controlled by a signal from the voltage controller and applies the commanded voltage to the motor.
5. The motor begins to rotate and accelerate.
6. When the motor feedback speed approaches the speed command, the voltage command from the speed controller decreases.
7. The motor torque decreases, and the acceleration is gradually reduced.
8. The gap between the feedback speed and the speed command becomes even smaller, and the voltage command from the speed controller decreases.
9. The motor torque becomes lower than the load torque, and the motor decelerates.
10. The difference between the feedback speed and the speed command becomes larger, and the voltage command from the speed controller increases.
11. The motor accelerates.

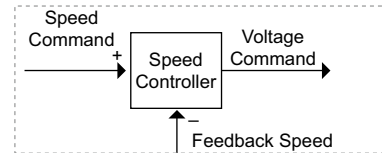


Fig. 4.2 Speed Controller

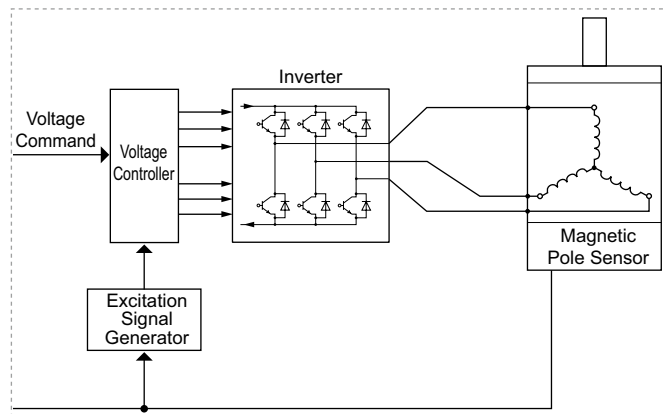


Fig. 4.3 Voltage Controller

Thus, the speed is controlled by repeatedly accelerating and decelerating as the motor rotation speed follows the speed commands.

## 4.3 High Accuracy Drive Circuit Configuration and Roles

We will now explain the high-accuracy control performed by the drive circuit, such as increasing motor responsiveness and smoothing out the generated torque using sine wave drive. In addition to the basic drive circuit shown in Fig. 4.1, the current loop has been designed to exercise fine control over the motor current. In addition, to perform sine wave driving, the excitation signal generator is replaced with a rotor magnetic pole position calculator. Here, we will explain the blocks added to and changed within the basic drive circuit.

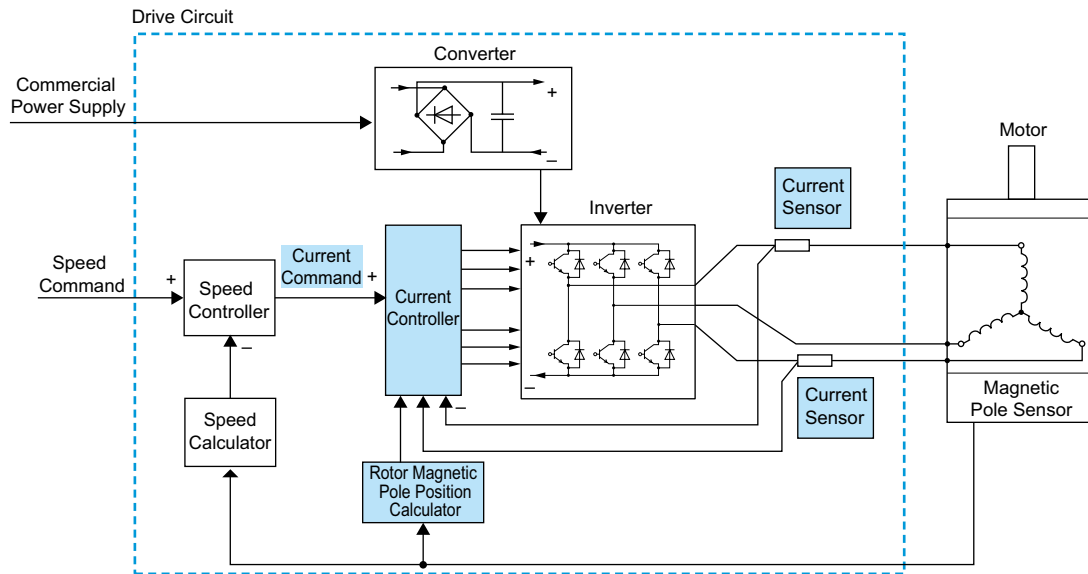


Fig. 4.4 High Accuracy Drive Circuit Configuration

### 4.3.1 Current Sensor

The current sensor detects the current flowing through the motor windings and provides feedback to the current controller. Because the sum of the currents input into the motor and the sum of the currents output from the motor are equal, in the case of a three-phase motor, it is possible to estimate the current in 3 phases by detecting the current in 2 phases.

Because the generated torque for brushless motors is proportional to the motor current, the torque generated by the motor can be estimated by detecting the motor current.

### 4.3.2 Rotor Magnetic Pole Position Calculator

The rotor magnetic pole position calculator continuously calculates the rotor position based on the signals from the hall effect ICs using an original algorithm. The continuous calculation of the rotor position allows for sine wave driving, which makes the torque ripples smaller and enables smooth operation.

### 4.3.3 Current Controller

The current controller performs excitation signal control for sine wave driving. In addition, it performs operations to compare the current command from the speed controller and the motor current from the current sensor and controls the motor current. Adding a current loop to the control circuit allows for control that decreases the deviation from the current command via instantaneous adjusting of the motor current.

## 4.4 Torque Control Methods

The torque for brushless motors is proportional to the motor current. As explained in “2.2.3 Brushless Motor Characteristics,” limiting the maximum value of the motor current results in places where the generated torque is constant.

Setting the maximum value for the current commands in a high accuracy drive circuit to  $I_1$ ,  $I_2$ , and  $I_3$  performs feedback control that makes the motor current equal to the set value, and the maximum torque of the motor becomes  $T_1$ ,  $T_2$ , and  $T_3$ , as shown in Fig. 4.5.

In other words, limiting the maximum value of the motor current in a drive circuit allows the torque generated in the motor to be limited. This function is called the torque limiting function, and it allows for objects to be pushed with a designated torque value and prevents damage in gearheads and devices.

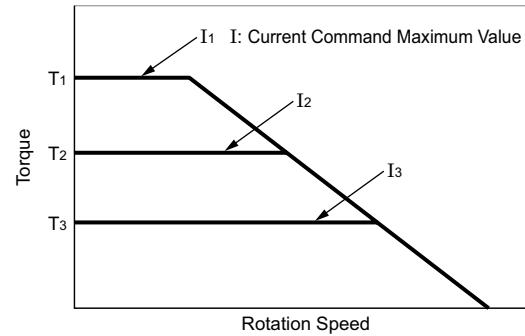


Fig. 4.5 Speed - Torque Characteristics (With the current limited)

## 4.5 Braking (Regenerative operation)

To decelerate and stop the motor, it is possible to simply cut off electrical power to the motor, but because it coasts to a stop, the stopping time is long. We will now explain a braking method that shortens the stopping time.

Brushless motors use permanent magnets in their rotors. If the motor speed is slower than the speed command, these act as a motor (power running) and generate driving torque, but if the motor speed is faster than the speed command, these act as a generator and generate braking torque.

The electrical power generated by the motor is called regenerative power, and an operating state that produces regenerative power is called a regenerative operation. The motor braking torque during regenerative operation is proportional to the current value, and the regenerative power is determined by the product of the braking torque and the motor rotation speed.

The motor speed during startup and stopping is shown in Fig. 4.6. Typical examples of motor operations that result in regenerative power including the following:

- During lowering operation when performing vertical operation for a load
- When overshooting after an inertial load accelerates up to speed (Fig. 4.6 ①)
- During the deceleration stop operation for an inertial load (Fig. 4.6 ②)

In particular, because the rotation speed is high during the overshoot (Fig. 4.6 ①) and at the start of deceleration (Fig. 4.6 start of ②), a large amount of regenerative energy is generated.

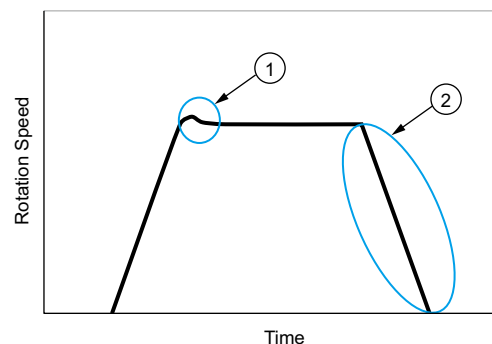


Fig. 4.6 Locations Where Regenerative Power is Generated during Operation

The current during braking operations is indicated by the red arrows in Fig. 4.7 and Fig. 4.8. During braking operations, the current flow generates a torque in the direction opposite of that generated during power running. This current direction is the same as that of a current produced by back EMF during power generating.

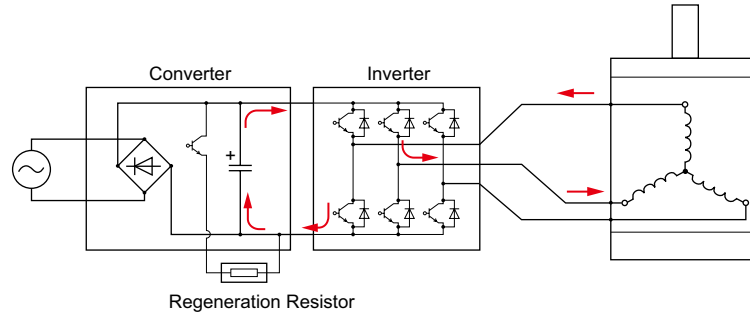


Fig. 4.7 Transistor ON

To control the braking torque, the transistor in the inverter is switched ON and OFF. When the transistor is OFF, the voltage applied from the driver disappears, but back electromotive force (back EMF) is generated. The current that flows due to these voltages passes through the diode and returns to the converter section in the driver, as shown in Fig. 4.8, but because there is a diode bridge, it cannot return to the power supply, so it is stored in a smoothing capacitor.

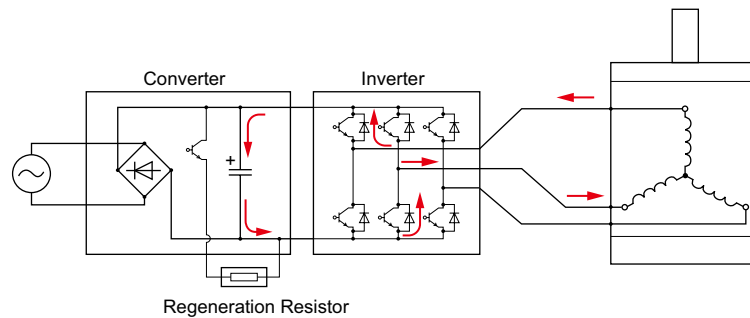


Fig. 4.8 Transistor OFF

The energy  $E$  stored in the capacitor is calculated using the following formula.

$$E = \frac{1}{2} C V^2 \quad (4.2)$$

$E$  : Energy [J]

$C$  : Converter smoothing capacitor capacity [F]

$V$  : Voltage between capacitor terminals [V]

The capacity  $C$  of the capacitor in the power supply section of the drive circuit is a fixed value. When a regenerative operation is performed, some of the regenerative energy is stored in the capacitor. For this reason, a voltage is appeared between the capacitor terminals according to the stored energy.

When the inertial load during braking operations is large or the load during vertical operations is large, the voltage between the terminals of the smoothing capacitor rises, which may lead to damage of the drive circuit components. To prevent drive circuit damage, the regenerative energy can be converted into heat energy via a resistor, or a power supply regeneration device can be used to return it to the commercial power supply. For small motors of several hundred watts, using a regeneration resistor is the typical method. When the voltage between the terminals of a smoothing capacitor exceeds the set voltage, current flows through the regeneration resistor, and the regenerative energy is consumed by converting it into heat energy.

# 5 Technology Used in Brushless Motors

Brushless motors have characteristics that make them excellent motors for speed control. In this section, we will explain the technology that allows the performance of these motors to be realized.

## 5.1 Wide Speed Control Range (Low-speed operation)

We will now explain the technology used to allow brushless motors to operate smoothly at low speeds.

### 5.1.1 Low Cogging Design

The pulsing torque one feels when rotating a motor shaft with one's finger while it is in a non-energized state is called the cogging torque. Brushless motors use permanent magnets in their rotors, and the magnetic energy stored in the air gap between the rotor and the teeth of the stator that face it changes depending on the rotor rotation position. The angle at which the rotor and teeth face each other repeatedly balances and imbalances the magnetic energy, generating cogging torque. In particular, if magnets with a high energy product are being used, high magnetic energy will also create high cogging torque.

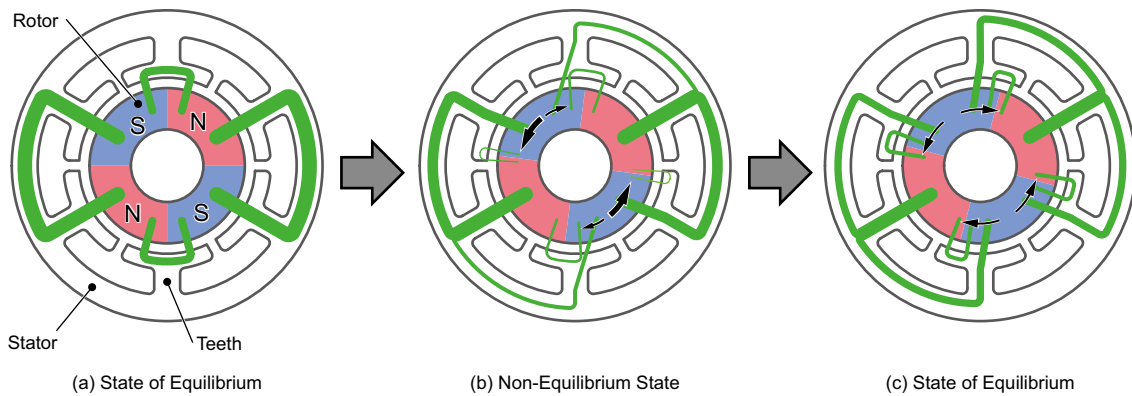


Fig. 5.1 Magnetic Energy States

We will now explain rotor angles and magnetic energy states using the example of a motor with 4 poles 6 slots shown in Fig. 5.1. The magnetic flux generated in the rotor magnets passes through the iron core of the stator along the paths indicated by the green lines, flowing from the north pole to the south pole. The thickness of the lines reflects the amount of magnetic flux, and the curvature of the lines towards the center reflects the unbalanced state of the magnetic energy. At this point, force is generated in the rotor in the directions (indicated by the black arrows) in which the magnetic flux attempts to flow so that it can become straight.

In the state shown in Fig. 5.1 (a), all of the magnetic flux aims towards the center, and the magnetic energy for each slot is well-balanced. In the state shown in Fig. 5.1 (b) where the rotor has been rotated clockwise  $7.5^\circ$ , the balance of the magnetic energy between the teeth facing the south pole is lost, and torques are generated with directions and magnitude matching those of the black arrows. The torque orientations are in the opposite directions, but torque is generated in the counterclockwise direction, where the generated torque is higher. In the state shown in Fig. 5.1 (c) where the rotor has been rotated clockwise another  $7.5^\circ$ , the balance of the magnetic energy between the teeth facing the south pole is lost, and torques are generated in the directions indicated by the black arrows. Torque generated in this state is negated by torque of the same magnitude traveling in the opposite direction, and a cogging torque is not generated.

Cogging torque is also generated when the motor is operating. While the motor is operating, it acts as a change in the load torque and inhibits smooth operation, so it is necessary to keep it low during the magnetic design. Up until now, a lot of research has been done on methods for reducing cogging torque. The main methods are as follows.

- Combining an appropriate number of teeth with an appropriate number of magnetic poles
- Making the rotor magnet arrangement or the magnetization of the magnet diagonal (rotor skew)
- Laminating the stator such that it twists (stator skew)
- Optimizing the shape of the magnets and stator
- Optimizing the waveform of the magnet magnetization

Combining an appropriate number of teeth with an appropriate number of magnetic poles is the most effective method for counteracting cogging torque. In general, the cogging torque period per motor rotation is the least common multiple of the number of magnetic poles and the number of teeth. In addition, the larger the least common multiple is, the lower the cogging torque becomes.

Fig. 5.2 shows a comparison of the cogging torques for an 8-pole 12-slot motor and a 10-pole 12-slot motor. The number of cogging torque cycles per motor rotation is 24 for the 8-pole 12-slot motor and 60 for the 10-pole 12-slot motor. The cycles generated by the 10-pole 12-slot motor are fine, and it is clear that the cogging torque decreases in amplitude.

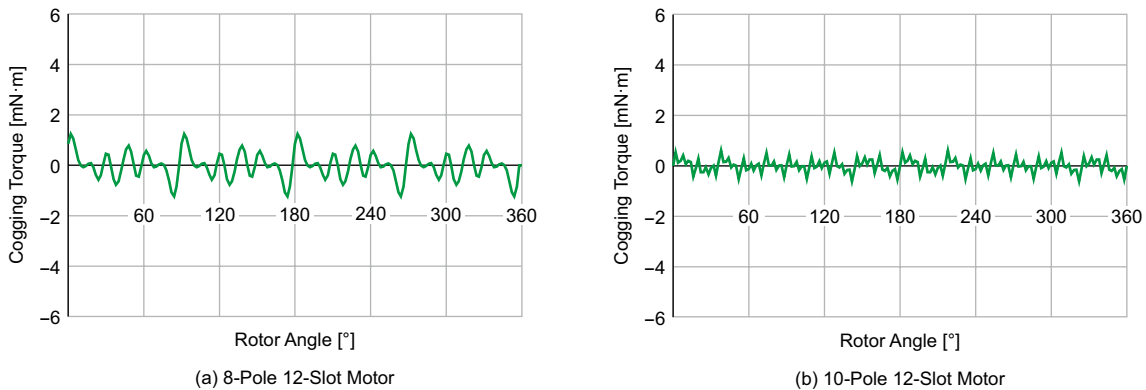


Fig. 5.2 Cogging Torque

### 5.1.2 Sine Wave Drive

Utilizing sine wave drive decreases the size of the torque ripples, and smooth operation is possible even during low speed rotation. While the principle is explained in “3.2.2 For a Sine Wave Drive System,” here we will explain the prerequisites that form the crux of this principle.

#### a. The Magnetic Flux Density That Acts on the Windings

The magnetic flux density that acts on the windings should ideally change so that it is a true sinusoidal curve, as shown in Formula (3.2). If distortion occurs in the sine waves, torque ripples are generated in the motor, which causes speed ripples. The methods for creating the ideal waveform for the magnetic flux density are the same as the methods for reducing cogging torque, and include the following.

- The optimum combination of number of teeth and number of magnetic poles
- Applying rotor skew or stator skew
- Optimizing the shape of the magnets and stator
- Optimizing the waveform of the magnet magnetization

However, because the shape that reduces the cogging torque is not the same as the shape that allows for the optimal magnetic flux distribution to be obtained, the design of the magnetic circuit takes balance into consideration.

### b. The Motor Current Consists of Sine Waves

As shown in Formula (3.6), it is ideal that the current that flows through the motor consist of sine waves. Just as with the magnetic flux density, if distortion occurs, torque ripples are generated, which causes speed ripples. To create the ideal current waveform, fine and accurate detection of the rotor magnetic pole positions is necessary. At Oriental Motor, intermittent processing of the hall effect IC signals using software allows us to obtain rotor magnetic pole position information at a high resolution.

### 5.1.3 Speed Detection Accuracy

Brushless motors use speed calculators to convert the signals from the hall effect ICs into rotation speed and obtain information about the motor speed. Low-speed operation of a motor widens the signal detection intervals from the hall effect ICs, as shown in Fig. 5.4, and the motor speed detection value changes periodically. If there are ripples in the feedback speed detection value, ripples will occur in the voltage (current) commands from the speed controller, which results in ripples in the motor speed.

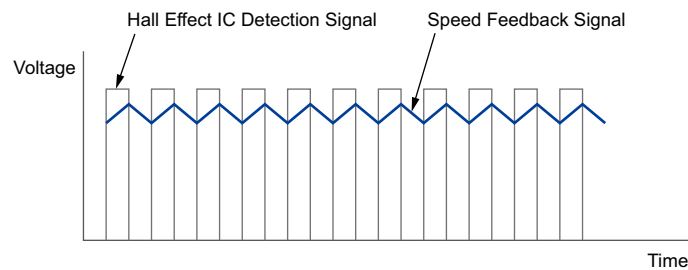


Fig. 5.3 Fast Motor Speed

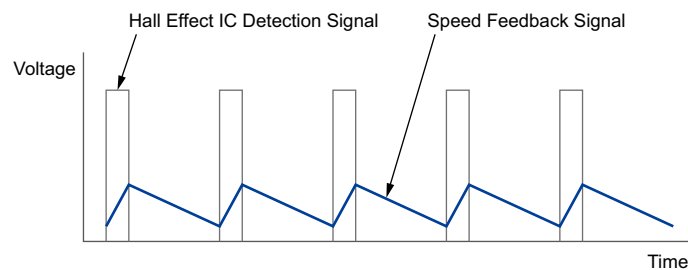


Fig. 5.4 Slow Motor Speed

Oriental Motor's brushless motors have increased the hall effect IC signal frequency by a factor of 2.5 by increasing the number of magnetic poles in the rotor from 4 to 10. This makes the feedback signals during low-speed operation smooth, reducing the ripples in the motor speed.

Because brushless motors use sensors for detecting magnetic poles, they have not been suited to low-speed operation. However, improvements in magnetic analysis technology, software signal processing technology, and drive technology have allowed the conventional lowest speed of 300 r/min in 4-pole motors to be lowered to 80 r/min. In addition, the output torque is constant even at low speeds, enabling control at a wide range of speeds, from low speeds to high speeds.

## 5.2 Wide Speed Control Range (High-speed operation)

Hall effect IC signal waveforms and motor current waveforms are shown in Fig. 5.5.

Compared to 500 r/min, with regards to the hall effect IC signals, lag in the current waveforms and an increase in motor current can be observed at 1000 r/min.

When performing driving for brushless motors, voltage is applied to the windings in accordance with the hall effect IC signals and excitation patterns. However, if the rotation speed increases, lag occurs in the current phases due to motor inductance. The lag that occurs in the current phases generates an ineffective electromagnetic force for the torque generated in the motor, decreasing the effective electromagnetic force. Because the motor performs control to maintain the rotation speed, the current is increased and the necessary torque is generated. Moreover, if the speed increases, the phase lag increases, and rotation ceases to be possible.

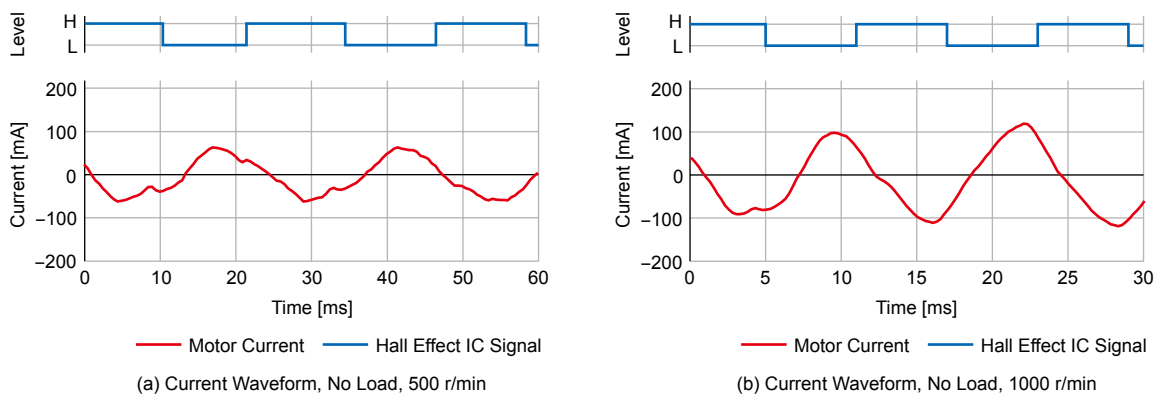


Fig. 5.5 Current Phase Lag

We will now explain the methods used to correct the current phase lag, which is necessary for making high-speed operation possible.

### 5.2.1 Output Torque Correction by Phase Control

Lead angle control allows for the output torque to be corrected by calculating the current phase lag according to the motor speed and advancing the voltage phase. The value by which the voltage phase is advanced is called the lead angle  $\alpha$ , and it can be calculated using the following formula.

$$\alpha = \tan^{-1}\left(\frac{\omega L}{R}\right) - \sin^{-1}\left(\frac{(K_e \omega)(L \omega)}{E_m \sqrt{(L \omega)^2 + R^2}}\right) \quad (5.1)$$

- $\alpha$  : Lead angle [rad]
- $\omega$  : Motor current angular speed [rad/s]
- $R$  : Winding resistance [ $\Omega$ ]
- $L$  : Inductance of windings [H]
- $K_e$  : Back EMF constant [V·s/rad]
- $E_m$  : Voltage generated by the driver [V]

However, performing a calculation this complex requires a CPU with high processing power. For this reason, instead of using the formula as-is to perform the calculation, an approximate formula for the lead angle is used in the calculation.

The relationship between the lead angle and the rotation speed is shown in Fig. 5.6. In areas where the lead angle is large, because it changes almost linearly with regards to the rotation speed, a linear approximation formula can be used to express the relationship between the lead angle and the rotation speed. Similarly, the relationship between the lead angle and the applied voltage can also be expressed as a linear approximation, so the lead angle can be calculated from the rotation speed and applied voltage. However, because using only the linear approximation results in the efficiency and torque decreasing due to excessive phase advancement during low-speed, high-load operation, in reality, a limit is imposed upon the lead angle value.

The advantages of this control system are that the circuit configuration is simple due to current loop not being needed, and that there are few motor control adjustment elements.

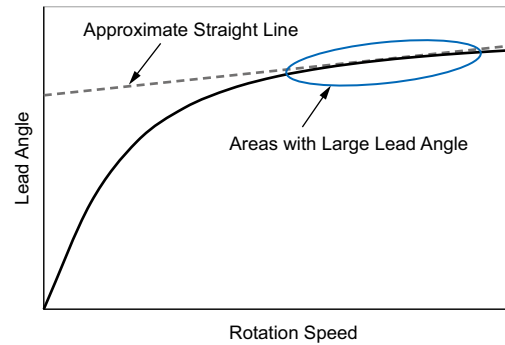


Fig. 5.6 Relationship between Rotation Speed and Optimum Lead Angle

## 5.2.2 Vector Control

Vector control is a control method that utilizes mathematical techniques to convert the currents that flow through the windings of a three-phase motor into a model equivalent to that of a DC motor, thereby simplifying control.

Currents that flow through phases U, V, and W of a brushless motor change constantly due to the motor torque and rotor rotation angle. Under these conditions, computational processing for current control is difficult. However, by converting a three-phase current into a 2-phase current, and fixed coordinates into rotational coordinates, it is possible to split the current into the torque-generating component (q-axis component of current) and the magnetic flux-generating component (d-axis component of current), regardless of the rotor rotation angle.

In this state, by constructing a current loop to retrieve the detection values from the torque-generating q-axis component of current, and the magnetic flux-generating d-axis component of current adhere to the command value, the output torque and the magnetic flux that passes through the windings (flux linkage) can be controlled at will.

Because the output torque and flux linkage can be controlled separately, the output torque and speed can be controlled with a high degree of responsiveness. In addition, by controlling the flux linkage, it is possible to achieve maximum efficiency control for energy-saving operation. It is also possible to improve speed - torque characteristics, such as maximum torque control and field weakening control.

An example of a current waveform being improved through vector control is shown in Fig. 5.7. Fig. 5.7 (a) shows the current waveform without vector control, and Fig. 5.7 (b) shows it with vector control. In the drive circuit, the motor current is controlled, such that it switches from negative to positive via the up edge of the hall effect IC output signal. Without vector control, lag can be observed in the motor current. In Fig. 5.7 (b), the hall effect IC signal up edge and current switching conform to one another, and the current phase lag disappears. In addition, performing vector control makes the motor current value smaller.

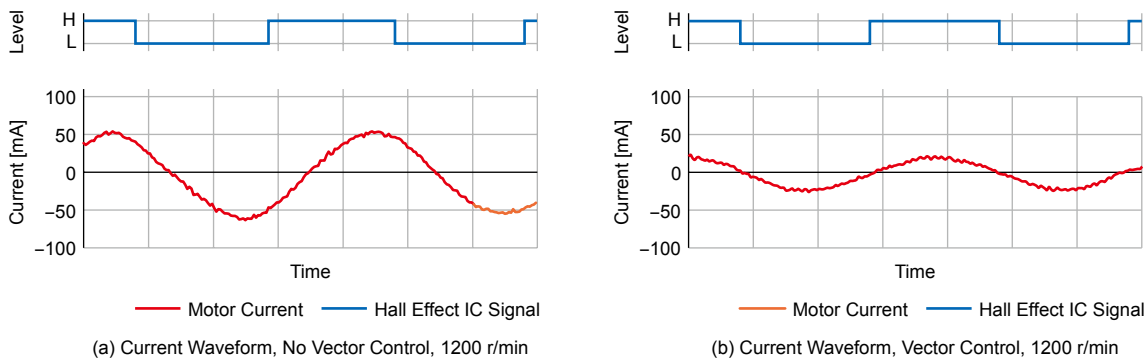


Fig. 5.7 Current Waveform during Vector Control

Displaying the states with and without vector control shown in Fig. 5.7 as current vectors using rotational coordinates creates a figure like that shown in Fig. 5.8. (When rotating counterclockwise)

When vector control is not performed, the orientation (indicated by the red broken line) in relation to the magnetic flux phase is less than  $90^\circ$ . In addition to the active current (q-axis component of current) component that acts as a torque, the motor current also includes a reactive current component that does not act as a torque.

When vector control is performed, the current flows in a  $90^\circ$  orientation in relation to the magnetic flux. Utilizing vector control to always keep the magnetic flux and current orientation at  $90^\circ$  eliminates current phase lag and reactive currents during high-speed operation and allows for efficient operation.

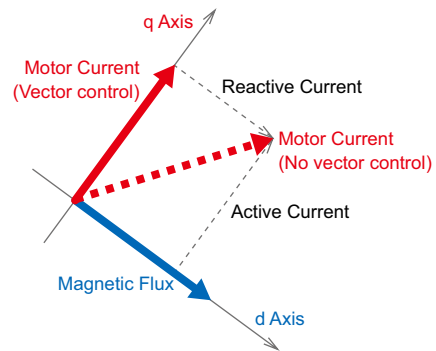


Fig. 5.8 Current Phase



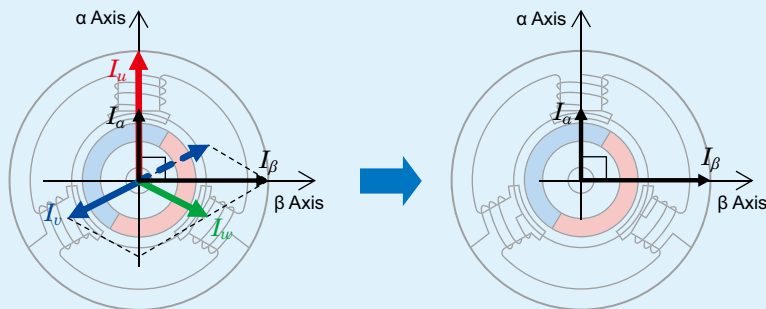
## Principles of Vector Control

1. Detect motor current values  $I_u$ ,  $I_v$ , and  $I_w$
2. Convert the three-phase current values into orthogonal 2-axis 2-phase current values [Clarke's transformation]

$$I_\alpha = I_u - \frac{1}{2} I_v - \frac{1}{2} I_w$$

$$I_\beta = -\frac{\sqrt{3}}{2} I_v + \frac{\sqrt{3}}{2} I_w$$

Values  $I_\alpha$  and  $I_\beta$  change for each rotor angle.



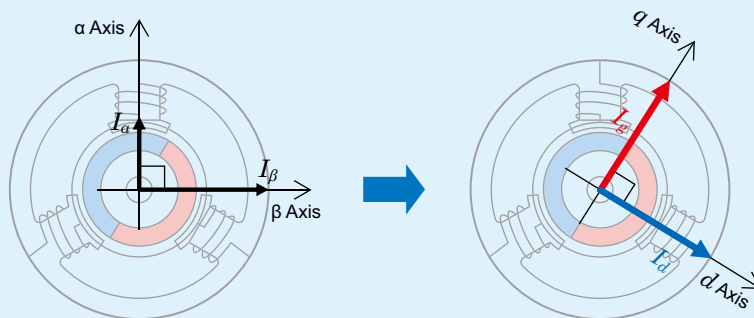
3. For the 2-phase current values, transform the coordinate system from fixed coordinates to rotational coordinates that synchronize and rotate with the rotor [Park's transformation].

By transforming the coordinate system so that the d-axis orientation is fixed in the direction of the magnetic field, the current can be treated as a direct current just as with DC motors that have rotating conductors, making the calculation much simpler.

$$I_d = I_\alpha \cos\theta + I_\beta \sin\theta$$

$$I_q = -I_\alpha \sin\theta + I_\beta \cos\theta$$

Values  $I_d$  and  $I_q$  are constants that are not related to the rotor angle  $\theta$ .



4. Compare the actual  $I_d$  (d-axis component of current) and  $I_q$  (q-axis component of current) with the command value to find the difference.
5. Control the applied voltage in the current loop such that the current command value matches  $I_d$  and  $I_q$ .

### 5.2.3 Field Weakening Control

Field weakening control refers to increasing the motor generated torque during high-speed rotation by weakening the magnetic flux of the part (field) that generates magnetic flux by controlling the d-axis component of the current.

The fundamental characteristics for brushless motors are sloping characteristics such as those shown in Fig. 5.9. The torque generated in the motor is proportional to the motor current, so the higher the speed, the smaller the current value. We will explain the reasons for this below.

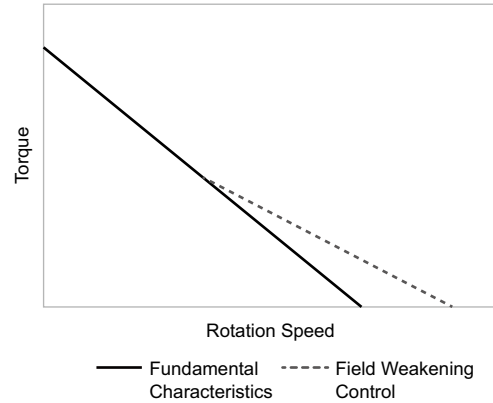


Fig. 5.9 Speed - Torque Characteristics

The voltage in each area when a brushless motor is rotating is represented by the below formulas.

$$V = R i + L \frac{di}{dt} + K_e \frac{d\theta}{dt} \quad (5.2)$$

$V$  : Power supply voltage [V]

$R$  : Winding resistance [ $\Omega$ ]

$i$  : Motor current [A]

$L$  : Inductance of windings [H]

$di/dt$  : Current rate of change

$K_e$  : Back EMF constant [V·s/rad]

$d\theta/dt$  : Rotor angular speed [rad/s]

The left side of Formula (5.2) indicates the applied voltage, the first term on the right side is the voltage applied to the winding resistance, the second term is the voltage due to the inductance component, and the third term is the back EMF.

From Formula (5.2):

$$i = \left( V - L \frac{di}{dt} - K_e \frac{d\theta}{dt} \right) / R \quad (5.3)$$

As indicated by Formula (5.3), if the motor rotation speed increases, the inductance component causes an increase in the voltage drop and the back EMF rises, decreasing the motor current. For this reason, the brushless motor speed - torque characteristics are sloping characteristics such as shown in Fig. 5.9.

By performing field weakening control during high-speed rotation, making the current flow in the d-axis negative direction, and weakening the field's magnetic flux, it is possible to lower the back EMF generated in the windings. Because the current becomes larger when the back EMF decreases, the generated torque increases. This allows the speed range used during high-speed operation to be expanded (Fig. 5.9).

## 5.3 High-Accuracy Speed Control

### 5.3.1 Speed Regulation

Speed regulation is an important specification for motors used for speed control.

Speed regulation is the rate of speed variation when the load torque, power supply voltage, ambient temperature, or other factors in the usage environment change while the motor is operating at a set speed. Oriental Motor's specification uses the rate of speed variation at the rated rotation speed when the following conditions are changed. Therefore, if the rated rotation speed is 3000 r/min and the speed regulation is  $\pm 0.2\%$ , the speed variation is  $\pm 6$  r/min.

Since speed fluctuation range depends on sensor detection accuracy, even if the operation speed is not 3000 r/min, the speed variation amount will still be approximately  $\pm 6$  r/min.

- With Load: When a rated load is applied, assuming a no-load state
- With Voltage: When the voltage changes within the allowable range, assuming a rated voltage
- With Temperature: When the temperature changes within the ambient operating temperature range, assuming an ambient temperature of 25°C

A brushless motor controls the motor speed in a closed loop, based on the feedback speed calculated from the hall effect IC signals. The increased number of signals from the Hall effect IC due to the rotor's multipolarity increases the detection accuracy of the rotation speed, resulting in low speed regulation, and allowing for operation at a speed close to the command speed.

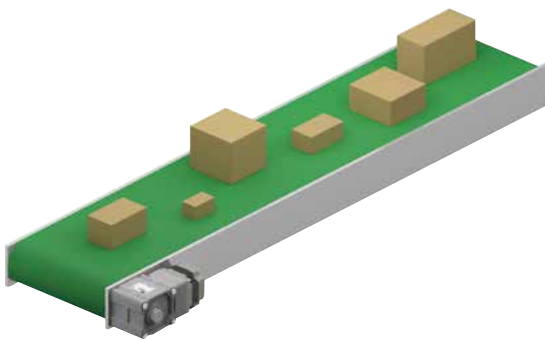
With inverters that do not have a speed detector and perform sensorless speed control, rotation speed changes due to the changes in the load torque.

Table 5.1 Speed Regulation with Load

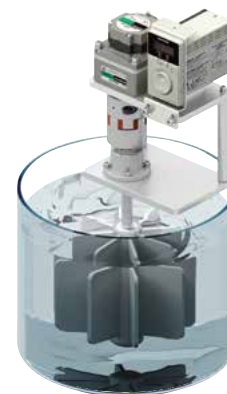
Type	Series	Regulation with Load
Brushless Motors	<b>BXII</b> Series	$\pm 0.05\%$
	<b>BLE2</b> Series	$\pm 0.2\%$ *
	<b>BMU</b> Series	$\pm 0.2\%$
AC Speed Control Motor	<b>DSC</b> Series	$\pm 1\%$ (Reference value)
Inverter	Combined Motor <b>KIS</b> Series	$-0.8\%$ (Vector control reference value)

\*When digital setting is used

Due to accurate speed regulation, stable operation is possible through a conveyor with variable loads and weights, an agitator or discharge pump in which the liquid viscosity changes, and so on. In addition, this is appropriate for coating, heating, and other applications in which a fixed processing time is desired during conveyance.



(a) Conveyor



(b) Agitator

Fig. 5.10 Application Examples



## Differences between Speed Regulation and Flutter Characteristic

Besides speed regulation, flutter characteristic is another characteristic that demonstrates motor speed stability.

- Speed Regulation: The average speed fluctuation ratio generated when the usage environment changes
- Flutter Characteristic: The speed ripple ratio for the average speed during rotation at a constant speed

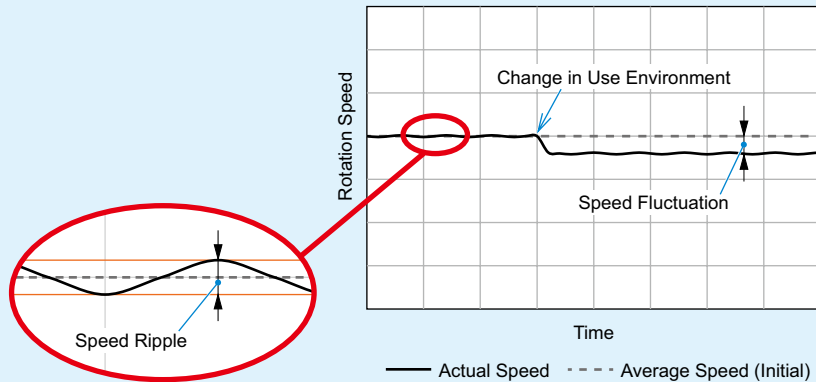


Fig. 5.11 Motor Speed Waveform

Speed fluctuation refers to the average speed of the motor itself changing, while speed ripples refers to the actual breadth of the speed changes when the average speed is constant.

Speed ripples are generated by torque ripples during a single motor rotation or by performing speed control. With image inspection equipment, they appear as screen shaking, and with coating equipment, they appear as coating inequalities.

### 5.3.2 High Reliability

We previously explained that because brushless motors control the motor speed in a closed loop based on the feedback speed calculated from the hall effect IC signals, the speed regulation is low and stable operation is possible. Because the motor speed is always being monitored, if for some reason an excessive load is applied and the speed decreases, or if the motor stops, an alarm signal is output, making it possible to detect malfunctions.

In addition, by utilizing overload information and the overload warning function, it is possible to detect increased loads before the overload alarm activates. This allows the prevention of sudden production line stoppage and for systematic maintenance.

## 5.4 Stable Stop Position

When performing high-accuracy positioning operations, in general, stepper motors and servo motors are used for their excellent position accuracy. However, depending on the working conditions and usage methods, it may be possible to satisfy the requirements for position accuracy even with simplified positioning operations with inexpensive motors for speed control or AC motors.

When stopping conveyed objects and rotated objects at a target position is desired, speed controllers and drivers with an instantaneous stop function are used. However, to detect conveyed objects, it is necessary to install a sensor at the stop position and perform control with a programmable controller and so on.

When a stop signal is input, the motor overruns and stops due to the effect of the rotor moment of inertia and the load moment of inertia. At this time, the overrun amount decreases according to the level of friction torque in the device.

### 5.4.1 Overrun Amount

The braking characteristics for the AC speed control motor **DSC Series 25 W** and the brushless motor **BLE2 Series 30 W** are shown in Fig. 5.12.

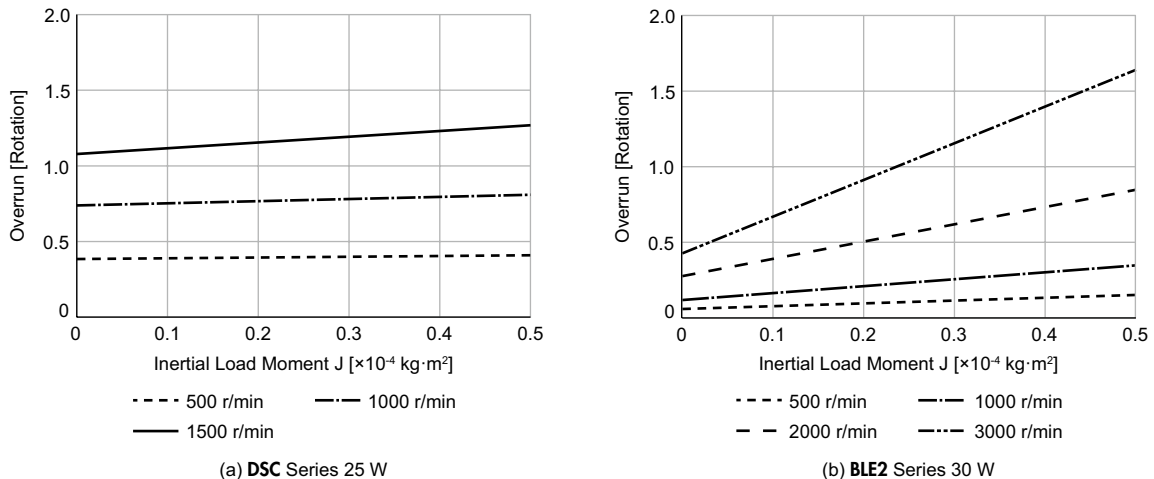


Fig. 5.12 Braking Characteristics

These braking characteristics show the relationship between the load inertial moment and the overrun amount (average value) when there is no friction load. Since the rotational energy is greater at high speeds or with a large inertial load, the overrun amount will also increase.

### 5.4.2 Variation in the Overrun Amount

Both AC speed control motors and brushless motors have variation in their overrun amounts. Fig. 5.13 shows the overrun amount variation when the motors repeatedly operate and brake 100 times with the load inertial moment J set to  $0.251 \times 10^{-4}$  kg·m<sup>2</sup> and the rotation speed set to 1000 r/min.

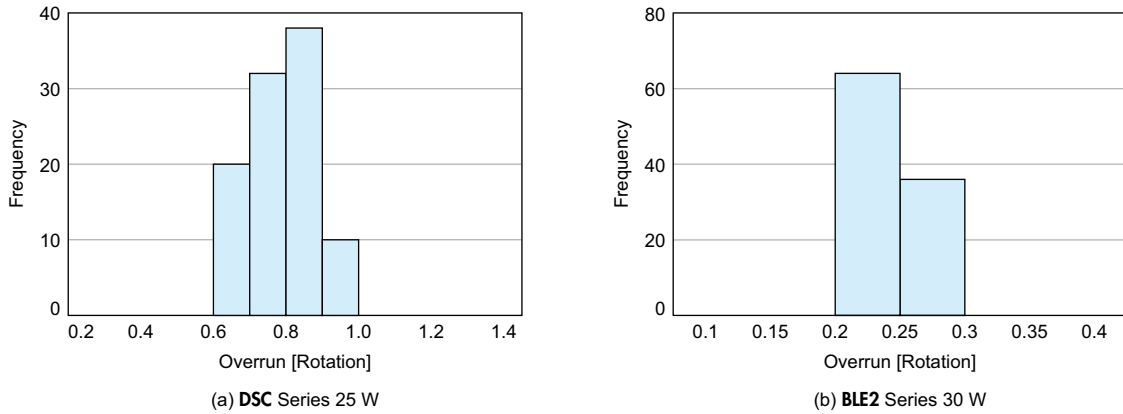


Fig. 5.13 Variation in the Overrun Amount

Many AC speed control motors and brushless motors are used in combination with gearheads. For example, when combined with a gearhead with a reduction gear ratio of 10, the average overrun amount and its variation measured at the gear shaft become the values shown in Table 5.2. 1 to 2° of backlash in the gear should be added to these values.

Table 5.2 Average and Variation of Overrun Amount

Target Products	Overrun Amount Average Value	Variation in the Overrun Amount
<b>DSC Series 25 W</b>	0.078 Rotations (28.08°)	±0.015 Rotations (±5.40°)
<b>BLE2 Series 30 W</b>	0.024 Rotations (8.64°)	±0.003 Rotations (±1.08°)

The differences in the average and variation of the overrun amount.

### 5.4.3 AC Speed Control Motor Braking Method

AC speed control motors control the voltage applied to the motors via triac-based firing angle control. When a brake signal is input, the triac switches OFF, and the thyristor turns ON for a fixed amount of time. As indicated by the red arrows in Fig. 5.14, an in-phase current that has undergone half wave rectification in the main winding (L) and auxiliary winding (S) of the motor flows through the diode. This causes DC braking (dynamic braking) to be performed, which stops the motor instantaneously.

Due to the timing of the brake signal input in the power supply voltage phase, the time when the braking current begins to flow (braking start time) lags behind the power-supply frequency by one cycle at most. For this reason, variation occurs in the overrun amounts.

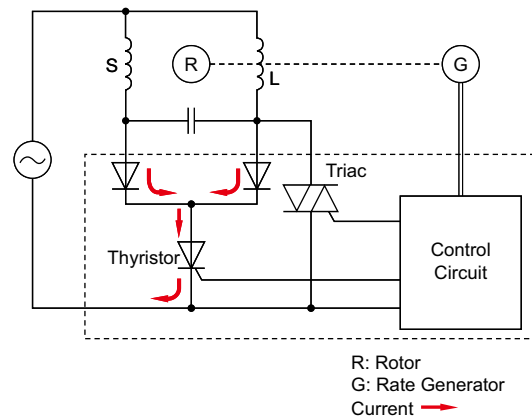


Fig. 5.14 DC Dynamic Braking

The relationship between the operation signal, the braking current, and the motor speed is shown in Fig. 5.15. Comparing the left and right figures, a gap of one power supply frequency cycle can be observed from the time when the operation signal switches OFF (brake signal ON) until the braking start time and the motor stops.

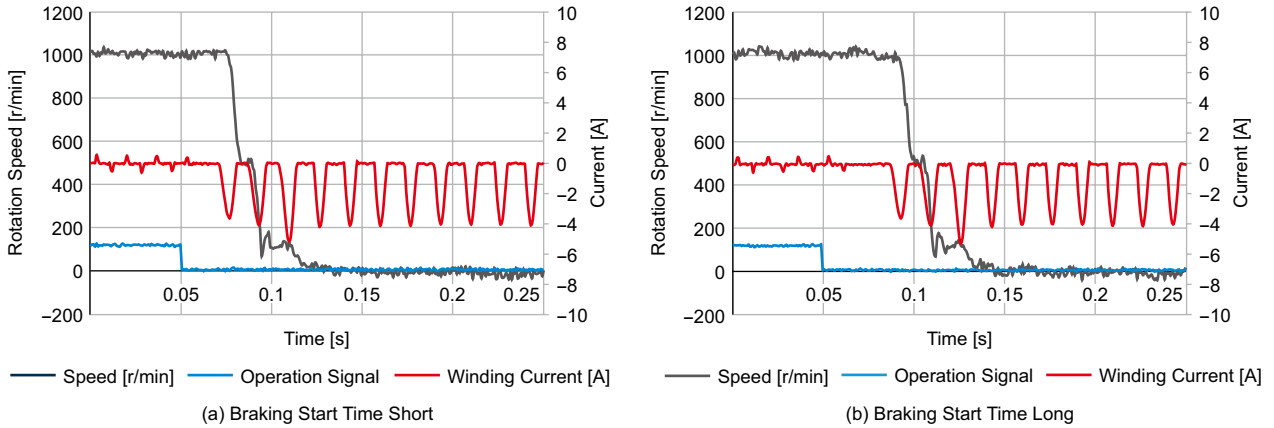


Fig. 5.15 Braking Waveform AC Speed Control Motor

### 5.4.4 Brushless Motor Braking Method

As explained in “4.5 Braking (Regenerative operation),” a brushless motor works as a generator during braking, and braking torque is generated by converting the rotational energy into electrical energy as shown in Fig. 5.16. If you look at Fig. 5.17, regeneration current flows through the windings directly after the operation signal switches OFF (brake signal ON). Because braking torque can be generated without being affected by the timing of the brake signal input in the power supply voltage phase, the stop position is stable.

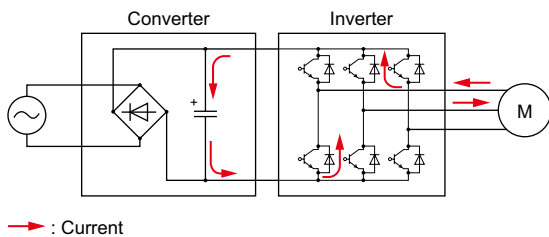


Fig. 5.16 Regenerative Braking

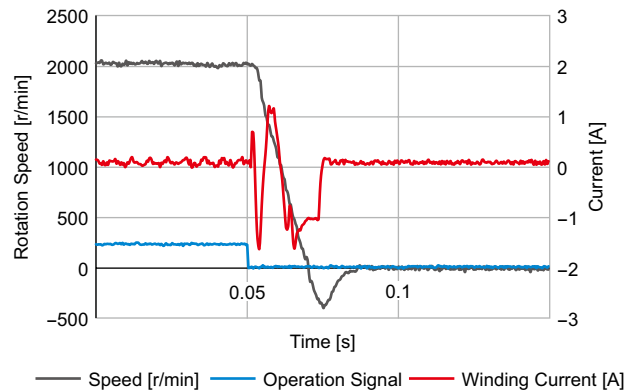


Fig. 5.17 Braking Waveform of a Brushless Motor

## 5.5 High-Efficiency, Energy-saving

According to the World Energy Outlook 2016 published by the IEA (International Energy Agency), over half of the world's total power consumption is motor-related. Reducing energy consumption is a global issue, and with regards to making motors more highly efficient, International Standard IEC 60034-30-1 defined efficiency classes aimed at induction motors from 120 W to 1,000 kW. Currently, classes of up to IE4 have been established, but an IE5 efficiency class is being planned as well.

Refer to Fig. 5.18.

Brushless motors with built-in permanent magnets do not fall under IEC 60034-30-1, but they are more efficient than three-phase induction motors, and the efficiency of a motor combined with a drive circuit exceeds that of the IE5 efficiency class (the expected values). Here, we will explain the loss reduction technology of brushless motors, primarily using Oriental Motor's **BMU** Series products as examples.

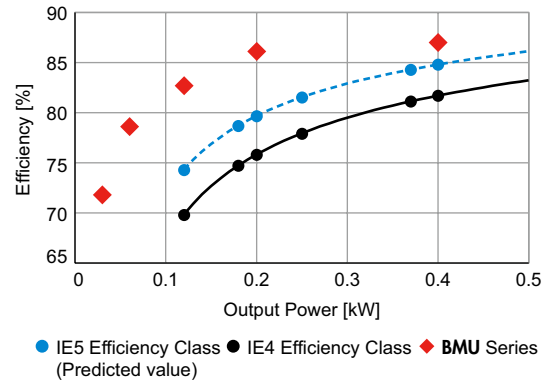


Fig. 5.18 **BMU** Series  
Combined Efficiency of Motor and Driver

### 5.5.1 Motor Loss

Loss categories are shown in Fig. 5.19. Motor loss is divided into copper loss, iron loss, stray load loss, and mechanical loss. In general, a large amount of motor loss is comprised of copper loss and iron loss. In addition, the smaller the motors, the larger the ratio of copper loss becomes, so it is important to take effective countermeasures to reduce loss based on the size of the motor.

Next, we will explain the main types of loss and technology for reducing loss.

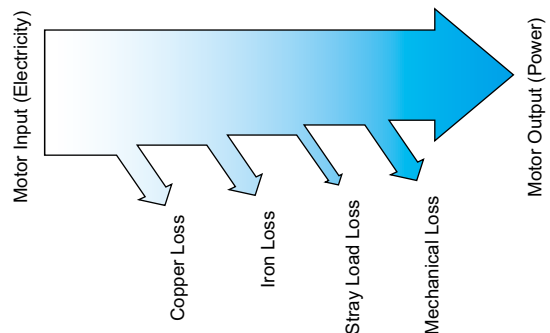


Fig. 5.19 Motor Loss

### 5.5.2 Copper Loss

Copper loss refers to joule loss resulting from currents flowing through copper wires, and it can be calculated using the below formula.

$$P_c = i^2 R \tag{5.4}$$

$$R = \rho_c \frac{l}{S} \tag{5.5}$$

$P_c$  : Copper loss [W]       $\rho_c$  : Conductor specific resistance [ $\Omega \cdot m$ ]  
 $R$  : Winding resistance [ $\Omega$ ]     $l$  : Conductor length [m]  
 $i$  : Winding current [A]       $S$  : Conductor cross-sectional area [ $m^2$ ]

As shown in Formula (5.4), the copper loss decreases as the current value and winding resistance value become lower. In addition, Formula (5.5) shows that the winding resistance value becomes lower the larger the conductor cross-sectional area becomes, allowing the copper loss to be reduced. For this reason, it is crucial to

wind a thick copper wire with a high space factor. The ratio of the slot cross-sectional area (the area of section of the stator with the copper wire windings) occupied by the copper wire is referred to as the space factor, and the higher this value is, the less unused space there is among the copper wire windings.

#### a. Reduction in the Current Value

Induction motors generate torque when an induced current flows through the cage type conductor inside the rotor due to the rotating magnetic field created by the stator. For this reason, winding currents contain currents used to generate torque and currents used to create induced currents. In addition, copper loss occurs in the stator windings and cage type conductor due to winding currents and induced currents.

Because brushless motors use permanent magnets in their rotors, induced currents are not necessary. Since only currents that generate torque are required, they can reduce winding current, unlike induction motors. Because there is no copper loss in the rotor and the copper loss in the stator windings can be reduced, there is less copper loss than with induction motors.

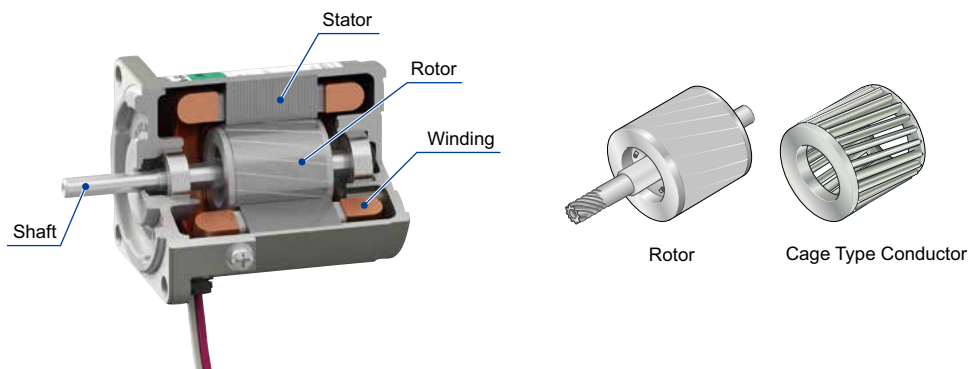


Fig. 5.20 Induction Motor Structure

#### b. Reduction in the Winding Resistance Value

Brushless motors developed in recent years, including the **BMU** Series, use neodymium sintered magnets with 6 times the energy product of conventional neodymium bonded magnets. Because the magnetic flux density from the rotor magnets has increased, the number of turns in the coil can be reduced compared to conventional products with the same output power.

However, because the magnetic flux density has increased, it is necessary to expand the tooth width, as shown in Fig. 5.21. To address this, a frameless structure that does not use a motor case is utilized, and the external diameter of the stator iron core is increased, which raised the slot area. In addition, technology for increasing the wire alignment was developed. These measures have made it possible to use a thicker conductor, allowing the winding resistance and copper loss to be reduced.

In addition, the increased magnetic flux density not only allows for the coil to have fewer turns, but it also allows the length of the stator core to be shortened.

The **BMU** Series, through high-performance magnets and increased space factor through improved stator shape and winding technique, has half the stator core length and 11% less copper loss compared to conventional products.

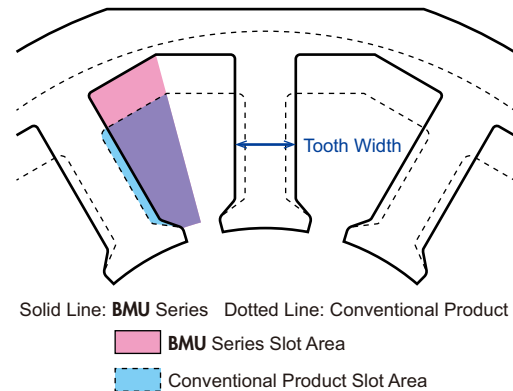


Fig. 5.21 Slot Area

### 5.5.3 Iron Loss

Iron loss is divided into eddy current loss and hysteresis loss. Eddy current loss occurs within the core due to the time variation of the magnetic flux density and flow through the stator core and rotor core. Hysteresis loss occurs in magnetizing energy resulting from alternating magnetization. They are represented by the following formulas.

$$P_i = P_h + P_e \quad (5.6)$$

$$P_h = k_h f B^{1.6} m \quad (5.7)$$

$$P_e = k_e t^2 f^2 B^2 m / \rho \quad (5.8)$$

$P_i$ : Iron loss [W]	$f$ : Field frequency [Hz]
$P_h$ : Hysteresis loss [W]	$B$ : Maximum magnetic flux density [T]
$P_e$ : Eddy current loss [W]	$m$ : Core mass [kg]
$k_h$ : Proportional constant	$t$ : Magnetic steel sheet thickness [m]
$k_e$ : Proportional constant	$\rho$ : Magnetic steel sheet specific resistance [ $\Omega \cdot m$ ]

As shown by Formula (5.7) and Formula (5.8), the elements related to motor iron loss can be divided into:

- the proportional constant and the specific resistance, which are determined by the magnetic steel sheet material
- the thickness of the magnetic steel sheet
- the field frequency, the maximum magnetic flux density, and the core mass, which are determined by motor design

To reduce the iron loss in the motor, a magnetic steel sheet that is thin, has low iron loss, has a high saturation magnetic flux density, and has good frequency dependence is ideal, but each of these characteristics has a trade-off. In addition, because there is a need to consider processability and cost, which characteristics are used depends on the required motor characteristics. Regarding design-related elements, it is necessary to optimize the magnets used and the balance between copper loss and iron loss.

#### a. Reduction in Hysteresis Loss

As shown by Formula (5.7), the hysteresis loss is equal to the maximum magnetic flux density raised to the power of 1.6 (to a power between 1.5 and 2 in some cases). However, because the maximum torque also decreases if the maximum magnetic flux density is low, it is necessary to choose a magnetic steel sheet with lower coercive force and low magnetizing energy to reduce iron loss while maintaining the motor performance.

#### b. Reduction in Eddy Current Loss

Motors with a high rotation speed and multipolar motors have high excitation frequencies for their magnetic steel sheets. As shown by Formula (5.8), because the eddy current loss is proportional to the maximum magnetic flux density, the field frequency, and the magnetic steel sheet thickness squared, using a thin magnetic steel sheet is effective for reducing the high frequency iron loss. In low-loss motors, magnetic steel sheets with thickness of 0.35 mm, 0.25 mm, and so on are used, and even thinner materials are being developed.

In addition, adding silicon (Si), which is non-magnetic and has a high resistance value, increases the specific resistance value of the magnetic steel sheet and makes it difficult for eddy currents to flow. However, at the same time, adding non-magnetic components decreases the maximum magnetic flux density, which decreases the maximum torque. Manufacturers of magnetic steel sheets are engaged in the development of products that increase the 2 contradictory properties through adjustment of the silicon (Si) amount, control of the crystalline structure, and so on.

The **BMU** Series utilizes high-performance magnets to make the stator length half that of conventional products, and combines this with high-performance magnetic steel sheets to reduce iron loss by 50%. Utilization of technologies such as these allows the **BMU** Series to have a total length that is 12% shorter than that of conventional products, with 33% higher output power and 7% higher efficiency.

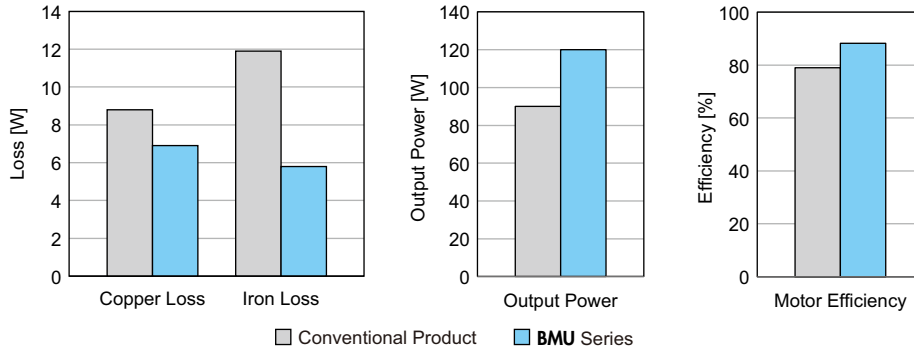


Fig. 5.22 **BMU** Series Loss Improvement

#### 5.5.4 Stray Load Loss

The loss that remains after subtracting copper loss, iron loss, and mechanical loss from the total motor loss is the stray load loss. Conventionally, this was treated as a loss whose causes were unclear. However, due to improvements in analysis technology in recent years, stray load loss gained visibility as local loss due to leakage flux and so on.

#### 5.5.5 Mechanical Loss

Mechanical loss in motors refers to friction loss from the bearing, oil seal, and other mechanical contact areas, and windage loss due to the types of cooling fans directly connected via shafts that are used in induction motors. With brushless motors, there is little loss, and cooling fans directly connected via shafts are not necessary, so mechanical loss can be suppressed.

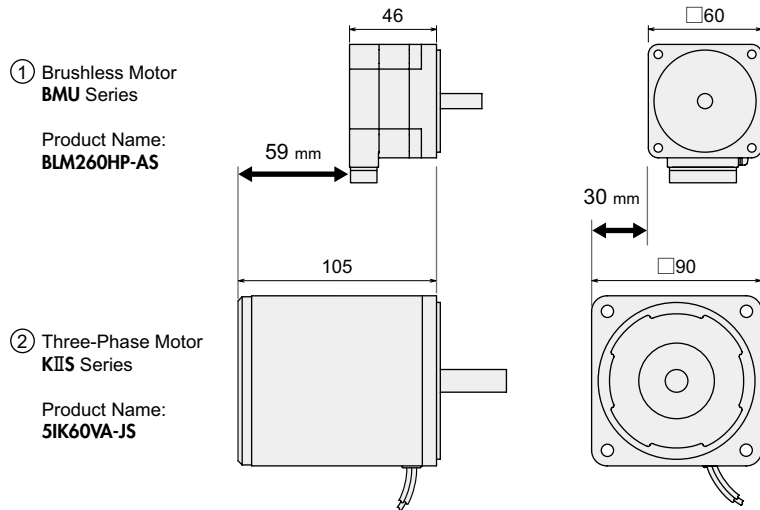
## 5.6 Small and Lightweight Motors

Brushless motors are smaller and lighter than three-phase motors while still offering the same rated output power. A motor’s rated output power is the output power at which the temperature rise in the parts used (mainly the wiring) satisfies the permissible temperature range when the motor is operated continuously under certain conditions determined by the specification, such as ambient temperature and supply voltage.

Due to the high efficiency, energy-saving technology explained in “5.5 High-Efficiency, Energy-saving,” brushless motors have little motor loss. The temperature rise in the motor balances loss with the heat release extent, so the less loss there is, the smaller the motor can be.

A comparison of the shapes and loss amount of a brushless motor and a three-phase motor with the same output power is shown in Fig. 5.23.

Because the motor is small and lightweight, this leads to the device being smaller and lightweight as well. In particular, with battery-driven vehicles, small size and lightness are emphasized because they are directly related to how long the vehicle can be driven.



	Output Power [W]	Total Length [mm]	Inclination Angle [mm]	Mass [kg]	Rated Loss [W]	Efficiency
①	60	46*	60	0.52	17.4	77.5%
②	60	105*	90	2.3	31.5	65.6%

\*Length from mounting surface of round shaft type (no gearhead)

Fig. 5.23 Comparison of Shape and Loss

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# Afterword

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Thank you for reading “Oriental Motor Technical Manual Brushless Motor Edition.”

The main objective of this manual is to assist readers' understanding of the structure and operation principles for brushless motors so that they can understand how they are different from AC speed control motors and inverters. Hopefully, readers understand how their characteristics are different from those of other motors, such as their wide speed range and speed accuracy.

When it comes to actually using brushless motors, one must possess knowledge not only of the motors' characteristics and features, but also product functions, the features of the reduction gears they are combined with, and so on. Regarding these, please consult catalogs and instruction manuals and use the appropriate devices for the brushless motor or other speed control motor in question.

It is our wish that this technical manual will prove useful to those reading it, helping to solve current issues and providing inspiration for future device development.





Oriental Motor (Europa) GmbH