# Understanding and Driving a Brushless DC Motor (BLDC)

In the vast world of electric motors, the Brushless DC Motor, commonly known as the BLDC motor, has emerged as a transformative innovation over the past few decades. While traditional brushed DC motors laid the groundwork for early electromechanical applications, the development and widespread use of BLDC motors have marked a new chapter characterized by superior precision, energy efficiency, and long-term reliability. No longer limited to industrial machinery or robotics, these motors now power a broad spectrum of modern technologies. From electric vehicles and compact cooling systems in laptops to personal mobility solutions like electric bikes and skateboards, BLDC motors play a crucial, though often unnoticed, role in driving the devices that shape contemporary life.

Despite their widespread use, BLDC motors are not plug-and-play devices like traditional brushed motors. Their operation relies on precise control logic, often implemented in embedded systems that must generate the correct sequence of voltages to the motor's windings. Unlike brushed motors where the mechanical brushes automatically commutate current, in a BLDC system, electronic commutation replaces physical contact, and the system must "know" the rotor's position to energize the correct windings.

This article will guide you through the fundamental principles behind BLDC motor operation, the practicalities of sensorless and sensored control, commutation strategies and the structure of an ESC. Whether you're an automotive engineer, an embedded systems enthusiast, or a curious student, you'll gain the insights needed to master this core element of modern electromechanics.

This article offers a comprehensive overview of the fundamental principles behind BLDC motor operation, covering both sensorless and sensored control techniques, commutation methods, and the architecture of an Electronic Speed Controller (ESC). Whether you're an engineer, a hobbyist, or simply someone with a curious mind, you'll discover the essential knowledge needed to understand and work with BLDC motors, one of the most important technologies driving today's innovations in motion control.

This guide follows an accessible, educational approach and deliberately avoids complex mathematical formulas to focus on clarity and practical understanding.

### A Simple Starting Point

A solenoid is a fundamental element in both physics and engineering, playing a crucial role in the study and application of electromagnetism. At its core, a solenoid is a coil of insulated wire wound tightly, typically around a cylindrical form or a metallic core. When an electric current flows through the wire, each loop produces a small magnetic field "B". When these loops are aligned in a tight helix, their fields add together, creating a well-defined north and south pole, just like a permanent magnet. Inside the coil, the field is especially uniform and concentrated. While a solenoid can function also in air, inserting a ferromagnetic core, such as iron, greatly amplifies the magnetic effect. The core becomes magnetized by the surrounding field and significantly increases the magnetic flux density, making the solenoid much more powerful.

A key concept associated with solenoids is the right-hand rule, which helps determine the direction of the magnetic field. By curling the fingers of your right hand in the direction of the current flowing through the coil's loops, your thumb will point in the direction of the magnetic field inside the solenoid, which also indicates the location of the north pole.

Understanding solenoids is essential for grasping more complex systems such as electric motors, magnetic relays, and inductors. In fact, the behavior of stator windings in a BLDC motor can be understood by first mastering the electromagnetic principles behind solenoids.

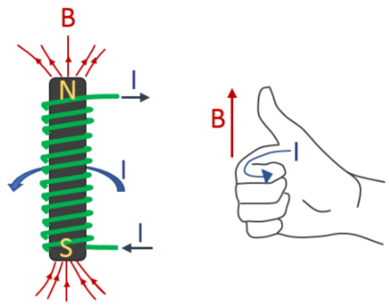


*Figure 1: Right-hand rule*

A brushless DC motor (BLDC) is composed of two primary components: the stator and the rotor. The stator, the stationary part of the motor, contains the windings that generate a rotating magnetic field when energized. The rotor, which is the rotating part, typically holds permanent magnets and spins in response to the changing magnetic field produced by the stator.

*Figure 2: Rotor (left) and Stator(right)*

To begin understanding how a BLDC motor works, consider a simplified example: imagine the rotor as a circular ring equipped with two permanent magnets facing inward, each oriented with opposite magnetic poles toward the center. The stator, in this basic model, consists of two solenoids or coils positioned to interact with the magnetic field of the rotor. This initial example serves as a foundational illustration to explain the core operating principle, as shown in the following figure.

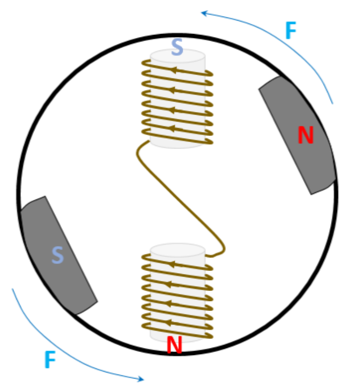


*Figure 3: Basic BLDC motor*

When a current “I” flows through the solenoids, it generates a magnetic field B, as discussed earlier. This magnetic field interacts with the permanent magnets on the rotor, creating a force that causes the rotor to begin rotating. It’s essential to recall that opposite magnetic poles attract, so:

- A solenoid with its south pole facing the rotor will attract the north pole of the nearest rotor magnet.
- Conversely, a solenoid with its north pole facing the rotor will attract the south pole of the rotor magnet.

As a result, the rotor will tend to align with the stator’s magnetic field. However, this interaction alone is not enough to create continuous rotation, but only a stable alignment.

If we reverse the current in the coils, the magnetic polarity reverses and repels the rotor’s current position, encouraging continued rotation. However, with only one coil and two possible polarities, we can only produce a very crude and limited form of rotation, and only if we know the rotor’s position very precisely.

This example demonstrates the fundamental principle of magnetic attraction and repulsion that drives all electric motors: the creation of rotating magnetic fields that “pull” the rotor along.

**Improved configuration**

To improve torque and make smoother rotation possible, we add two more stator coils spaced 120° apart. This creates a three-phase configuration. Now we can sequence current through these coils to produce a rotating magnetic field, rather than just toggling polarity.

The following figure illustrates the six commutation steps used to activate the three coils in a three-phase system, enabling a smoother and more continuous rotation compared to the previous example. Each coil activation advances the rotor by 60 degrees.

In steps 1 through 3, the three coils are energized one at a time in a sequential manner, as shown in the timing diagram on the right. From steps 4 to 6, the coils are again activated sequentially and exclusively, but with the current direction reversed, effectively inverting the polarity of each phase.

The basic principle is that current is driven through the coils in such a way as to generate a magnetic field, effectively creating magnetic poles that attract the permanent magnets on the rotor, allowing it to rotate. For example, in both step 1 and step 4, coil $L_1$ is the only one being energized, but with current flowing in opposite directions.

- In step 1, the upper part of $L_1$ presents a south magnetic pole to attract the rotor's north pole, while the lower part of $L_1$ presents a north magnetic pole to attract the rotor's south pole.
- In step 4, the current is reversed: the upper part of $L_1$ now presents a north pole to attract the rotor's south pole, and the lower part presents a south pole to attract the rotor's north pole.

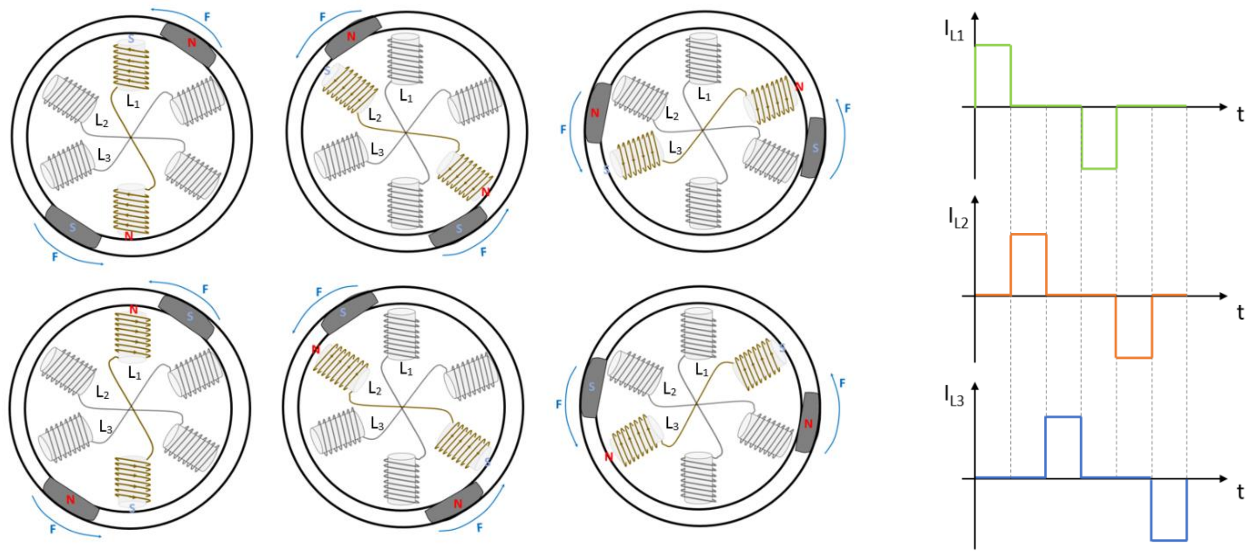


*Figure 4: Six step commutation*

### Real BLDC motor

Brushless motors can be designed in two main structural configurations: with the rotor located inside the stator windings (inner rotor), or with the rotor surrounding the stator windings (outer rotor). Each arrangement is suited to different mechanical and performance requirements.

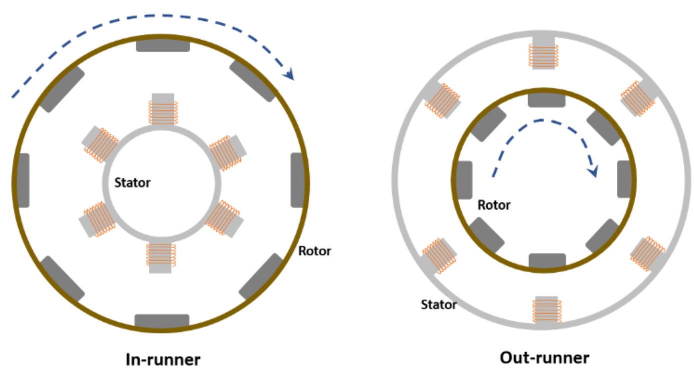


*Figure 5: Different structural configurations of BLDC motors*

Another key design aspect of BLDC motors is the number of stator windings, referred to as the number of phases. While it's possible to build brushless motors with various phase counts, three-phase configurations are by far the most common, especially in applications requiring smooth rotation and precise control. Exceptions exist: small cooling fans may use only one or two phases due to their simplicity and low cost.

The three stator windings in a typical three-phase motor are electrically connected in one of two topologies: star (Y) or delta (Δ). Regardless of the topology, there are three external terminals for motor control, and both the driving technique and electrical waveforms used in control remain essentially the same.

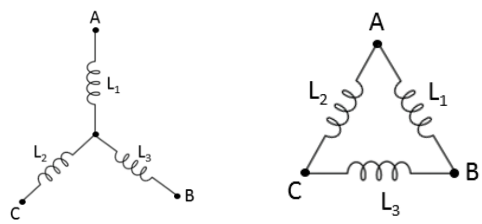


*Figure 6: Star and Delta topologies*

In addition to phase count, brushless motors are also characterized by their pole configuration, which refers to the number of magnetic poles in the rotor. The most basic three-phase BLDC motor features a two-pole design, where the rotor contains one north pole and one south pole. However, motors can also be constructed with a higher number of poles, requiring additional magnetic segments in the rotor and a corresponding arrangement of windings in the stator.

Increasing the number of poles generally enhances torque and low-speed performance, while lower pole counts are typically better suited for high-speed applications due to reduced switching frequency and mechanical limitations.

Let us consider the star (Y) configuration, although the principles discussed here apply equally to the delta (Δ) configuration. In this arrangement, the windings are interconnected in such a way that only two coils are energized at any given time. This design enables the motor to take advantage of both attractive forces between opposite magnetic poles (as previously described) and repulsive forces between like poles, which together contribute to efficient torque generation.

Another key detail is that, during each step of operation, one of the three coils remains unpowered and this unenergized coil is precisely the one aligned with one of the rotor’s permanent magnets. This positioning plays an essential role in sensorless control methods, such as back-EMF detection, but we will look at this aspect later.

The following figure illustrates one step of the commutation sequence. In this phase, coils $L_1$ and $L_3$ are energized, and the resulting current flow generates magnetic poles that simultaneously repel and attract the rotor’s permanent magnets.

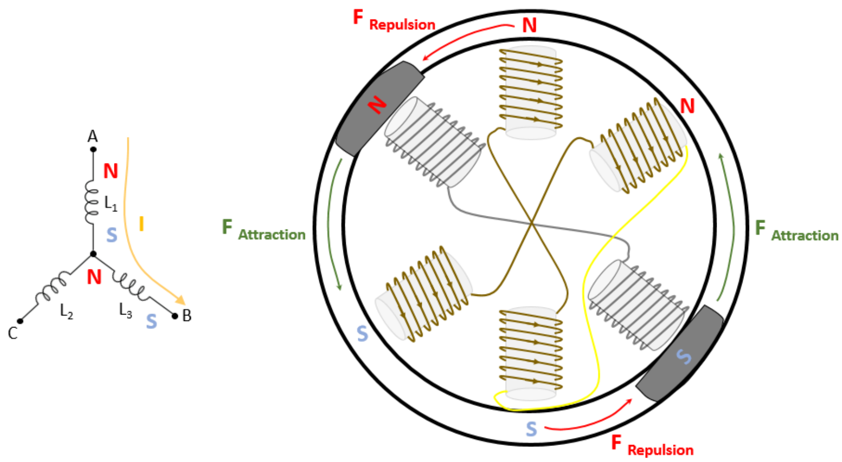


*Figure 7: Phase operation of a three-phase BLDC motor*

The figure below shows two consecutive steps in the six-step sequence that completes a full 360° electrical rotation of the rotor. As illustrated, in each commutation step:

- The coil before the rotor's magnet exposes a like pole, creating repulsion.
- The coil after the rotor's magnet exposes an opposite pole, creating attraction.

These two forces, repulsion from the previous phase and attraction to the next, combine to produce a torque vector that pulls the rotor forward, ensuring continuous rotation in the desired direction.

Even in this configuration, reversing the current polarity is necessary to generate the desired magnetic field.

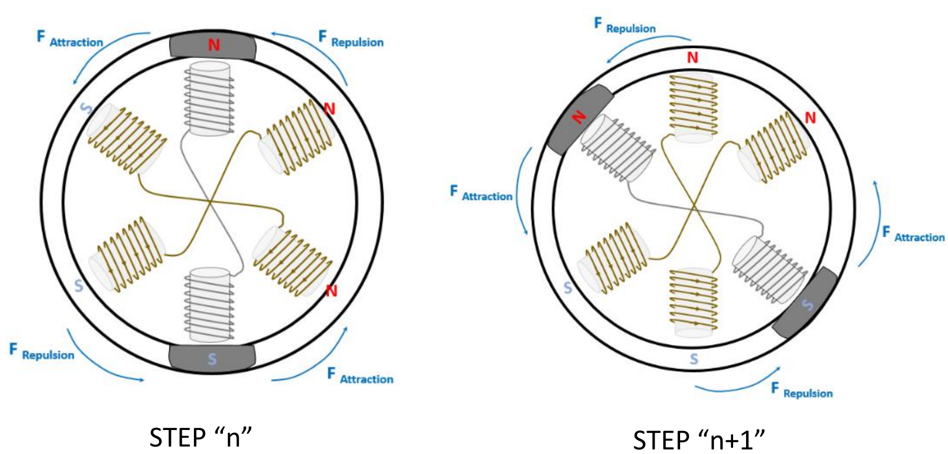


*Figure 8: Two consecutive commutation steps*

Here is a standard 6 step commutation phase table for a 3-phase BLDC motor with trapezoidal commutation. This type of control energizes two coils at a time, leaving the third floating, and rotates the rotor in 6 electrical steps per revolution cycle.

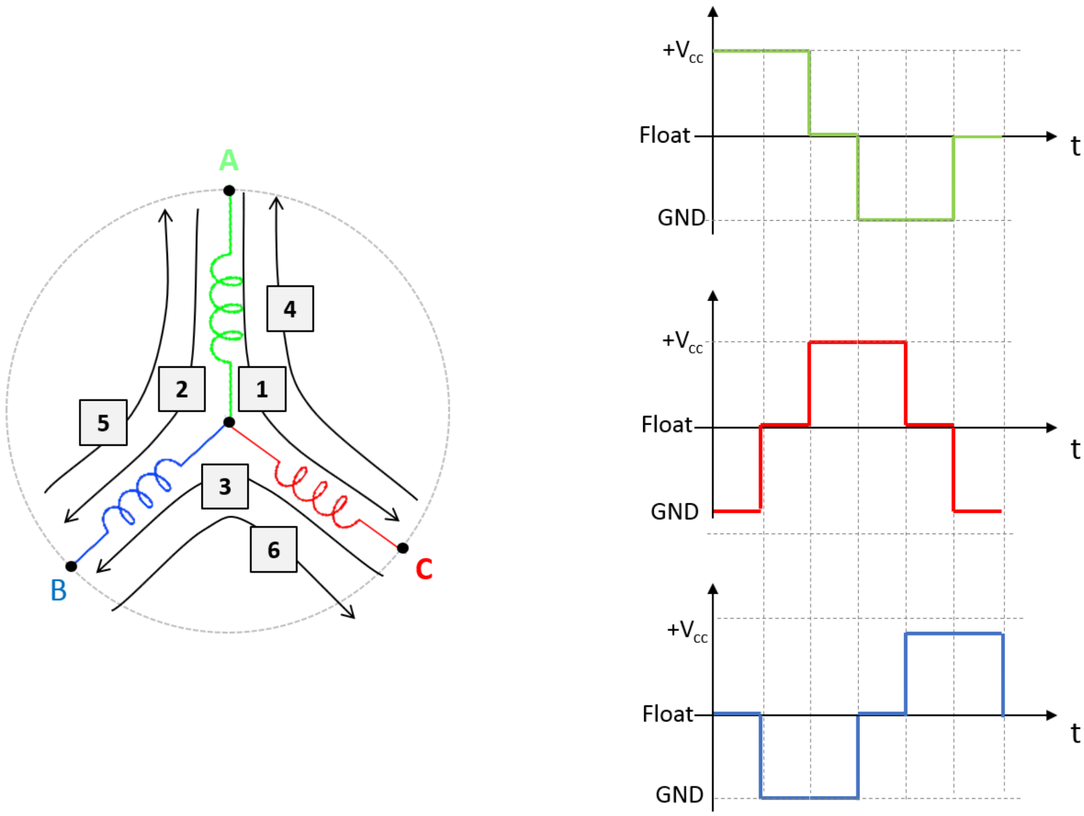


*Figure 9: Complete six step commutation sequence*

*Table 1: Six step clockwise commutation table*

| Step | Phase A | Phase B | Phase C | Current flow |
|---|---|---|---|---|
| 1 | +V | -V | Floating | A → B |
| 2 | +V | Floating | -V | A → C |
| 3 | Floating | +V | -V | B → C |
| 4 | -V | +V | Floating | B → A |
| 5 | -V | Floating | +V | C → A |
| 6 | Floating | -V | +V | C → B |

*Table 2: Six step counterclockwise commutation table*

| Step | Phase A | Phase B | Phase C | Current flow |
|---|---|---|---|---|
| 6 | Floating | +V | -V | B → C |
| 5 | +V | Floating | -V | A → C |
| 4 | +V | -V | Floating | A → B |
| 3 | Floating | -V | +V | C → B |
| 2 | -V | Floating | +V | C → A |
| 1 | -V | +V | Floating | B → A |

Where**:**

- +V: Phase connected to positive supply (high-side ON)
- -V: Phase connected to ground (low-side ON)
- Floating: Phase is not actively driven (neither high nor low)

The sequence illustrated causes the motor to rotate in a clockwise direction. Reversing the order of the steps (from step 6 back to step 1) will result in counterclockwise rotation. Each step advances the rotor by 60 electrical degrees, so a complete electrical cycle consists of six steps totaling 360°. In motors with more than two poles, a full electrical revolution corresponds to only a portion of a mechanical revolution, depending on the number of pole pairs.

The excitation sequence of the stator's electromagnets is arranged so that the rotor magnets are simultaneously attracted and repelled by the energized coils, yet they never reach the opposing pole. This happens because only the coils that have not yet been reached by the rotor are activated. In fact, the coil directly aligned with the magnet is turned off, while the next one in the rotation sequence is energized to attract the magnet, and the previous one is energized to repel it.

A helpful analogy to better understand this principle is illustrated in the figure below, the classic story of the donkey and the carrot.

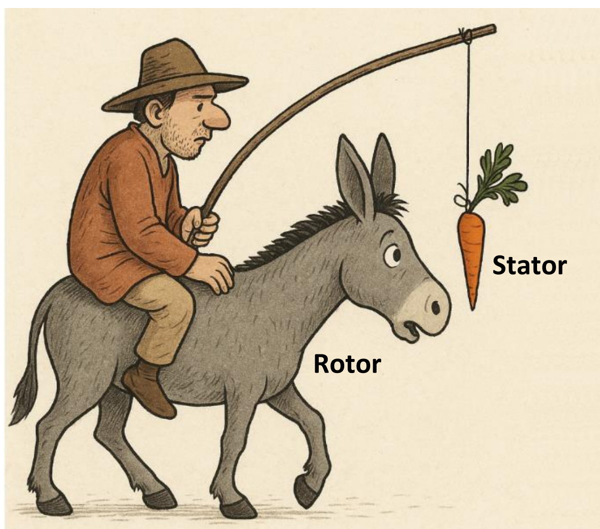


*Figure 10: Analogy with the story of the donkey and the carrot*

When utilizing multiple coils, always in even numbers, it is advantageous to adopt a commutation strategy that energizes all coils except those positioned directly opposite the rotor’s permanent magnets. This method boosts the overall magnetic flux interacting with the magnets, thereby increasing the motor's torque output without the need for significant structural modifications. Additionally, the more coils that are used, the smoother the rotor’s rotation becomes, leading to a more consistent and stable torque profile.

Great. Now that we understand how to drive the three-phase windings to rotate the motor, it becomes clear that, unlike a brushed DC motor, which only requires a power supply to operate, a brushless motor needs a dedicated driving circuit. A basic circuit diagram of this driver is presented in the following image.

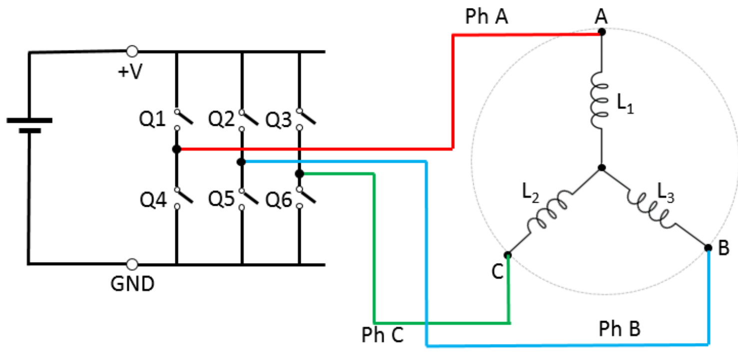


*Figure 11: Simple commutation circuit*

The switches labeled $Q_1$ to $Q_6$ must be turned on and off according to the Six-Step Commutation Table.

For instance, to execute "Step 2," switches $Q_1$ and $Q_5$ should be closed, enabling current to flow through phases $L_1$ and $L_3$, while all other switches remain open.

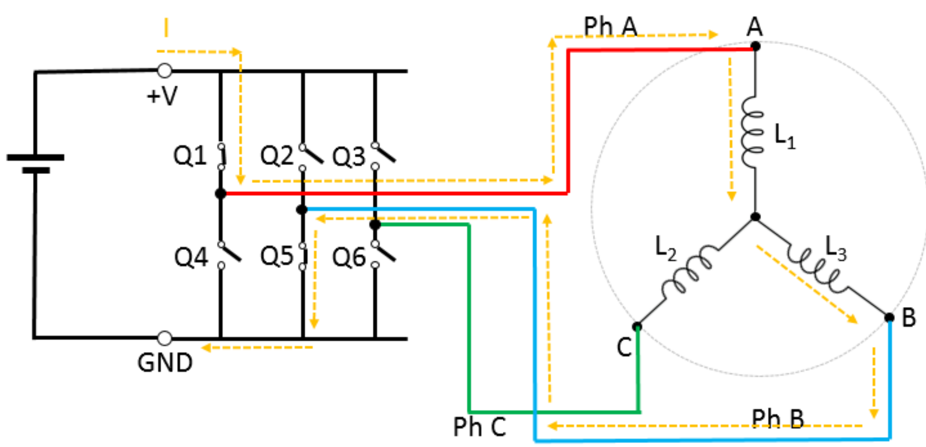


*Figure 12: Activation of coils L1 and L3*

In practice, the switches $Q_i$ are replaced by electronic components such as MOSFETs or IGBTs, which are used as high-speed switches. The figure below illustrates an implementation using power MOSFETs.

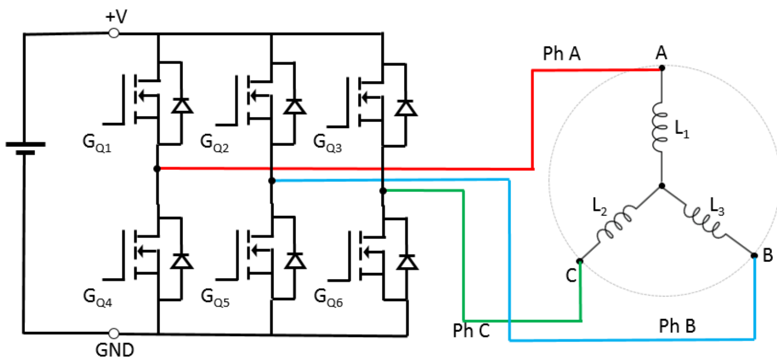

*Figure 13: Implementation of the commutation circuit*

The gate control signals $G_{Qi}$ are typically not simple digital signals 0 or 1 (OFF, ON), but rather PWM (Pulse Width Modulation) to allows regulation of the average current flowing through the coils.

It’s important to understand that in a BLDC motor, torque is proportional to the current flowing through the motor's windings. In simple terms: more current = more torque.

Moreover, using a high PWM frequency (usually between 10 and 30 kHz) along with accurate duty cycle modulation allows for a smooth current flow, even though the signal is composed of rapid switching pulses. This helps minimize torque ripple and mechanical vibrations, resulting in smoother motor operation. Additionally, since the gate PWM signals control both the high-side and low-side MOSFETs, precise timing is essential to prevent them from turning on simultaneously, an event that would cause a short circuit known as shoot-through.

So, if you want the motor to:

- Spin faster or slower,
- Accelerate smoothly,
- Maintain a specific load torque,
- Or operate safely within thermal limits,

... then controlling the current becomes essential.

PWM is a technique where instead of delivering a constant voltage to a load (like a motor winding), we switch the voltage ON and OFF rapidly, thousands of times per second. This rapid switching creates a pulsed waveform that can be averaged over time. If we switch ON 50% of the time and OFF the other 50%, we effectively deliver half the voltage as an average value.

In this context, it's helpful to explain the concept of "duty cycle." It represents the fraction of time a digital signal remains active (on or high) during one complete cycle (on + off) and is typically expressed as a percentage.

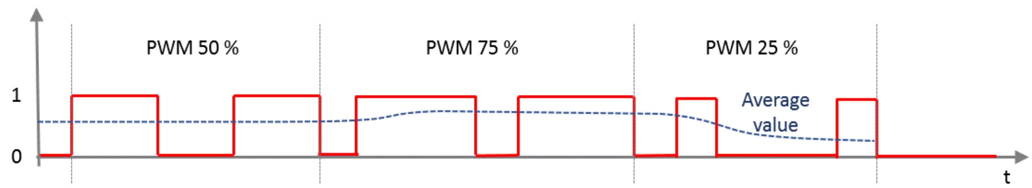


*Figure 14: Example of PWM signal*

So:

- A 10% duty cycle (ON 10%, OFF 90%) gives a low average voltage.
- A 90% duty cycle gives a high average voltage.
- A 100% duty cycle means full power, as if we applied the supply voltage directly.

The motor doesn’t react to the individual pulses because its coils (being inductors) smooth out the current over time. Instead, it responds to the average power delivered. Keep in mind that every physical system, including electronic ones, possesses inertia.

Think of the motor winding as a water pipe and the current as water flowing through it. If you open the valve fully (100% duty cycle), the flow is strong. If you open it halfway (50% duty cycle), the flow is reduced.

By adjusting the duty cycle of the PWM signal we control the average voltage and current seen by the motor coils and, as a result, we control the torque output of the motor.

This is especially important during: acceleration, load changes (to maintain constant torque), soft-starting (to avoid mechanical stress).

As already discussed, a BLDC motor is typically driven by a 3-phase inverter circuit, built using six MOSFETs (or IGBTs), forming a three-phase bridge. The commutation logic ensures that current flows through the correct two windings at any given time (since one winding is always off in “trapezoidal” 6-step commutation).

Now, imagine you want to control the power delivered to those active windings. Here’s how PWM fits in:

- One of the (two) active MOSFETs is switched rapidly using a PWM signal.
- The duty cycle of that signal determines how much current flows.
- The microcontroller can adjust this duty cycle in real-time based on speed demand, load, or current feedback.

The most common practice is:

- PWM the high-side MOSFET, while the low-side remains ON (or vice versa),
- The winding receives pulsed voltage, and thanks to its inductance, the current smoothly ramps up and down,
- The result is a nearly sinusoidal or trapezoidal current waveform, depending on control strategy.

PWM works best when its frequency is high enough so that the motor doesn't "feel" the ON/OFF pulses as vibrations or noise. That's why most BLDC controllers use PWM frequencies between 10 kHz and 30 kHz, high enough to be beyond human hearing and to ensure smooth current flow.

Despite the digital nature of PWM, the average voltage seen by the motor windings becomes analog-like due to the filtering effect of the inductance.

**Dead time between commutations**

In a BLDC PWM control system, timing is critical. Each pair of switches must be controlled so that:

- Both high- and low-side switches never turn ON at the same time (this would create a dangerous short circuit),
- A small "dead time" is introduced between turning one off and the other on.

Gate driver circuits (and some microcontrollers) provide this automatically.

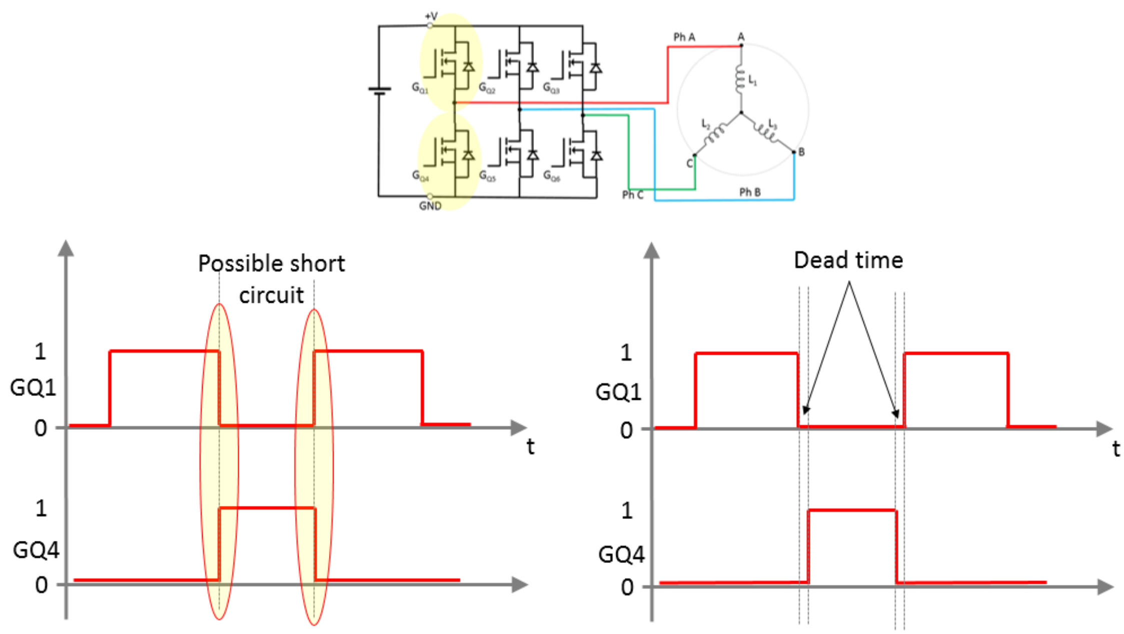


*Figure 15: Dead time to avoid short circuit*

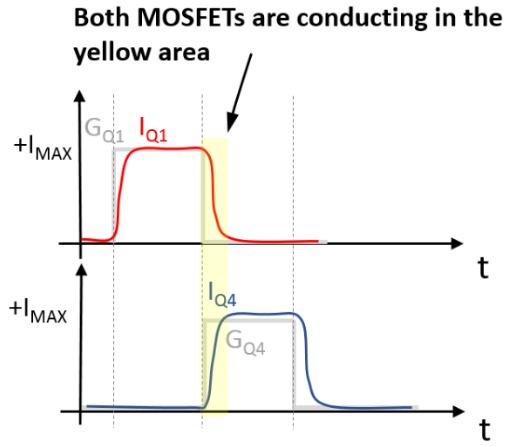


*Figure 16: Real waveform of current ($I_{DS}$) in the MOSFET*

## The Electronic Speed Controller - ESC

An Electronic Speed Controller (ESC) is an embedded electronic circuit that controls the speed, direction, acceleration and braking of an electric motor. A BLDC motor's stator contains a set of fixed windings, and its rotor is embedded with permanent magnets. To produce torque, the stator windings must be energized in a specific sequence, creating a rotating magnetic field that "pulls" the rotor along. This process is called commutation.

An ESC performs several important functions:

- Generates three-phase AC signals from a DC power source,
- Applies the right phase sequence at the correct time,
- Adjusts the motor speed via PWM (Pulse Width Modulation),
- Ensures safe operation through overcurrent, thermal, and voltage protections,
- Optionally provides feedback via communication protocols like UART, CAN, SPI, or I2C.

A BLDC ESC typically contains the following components:

- A microcontroller or digital signal processor (DSP) for logic and timing.
- Power electronics: MOSFETs or IGBTs arranged in a three-phase bridge (usually 6 switches).
- Gate drivers: To amplify control signals (comes from the controller) and drive the power switches.
- Current and voltage sensors for monitoring.
- Optionally, position sensors or back-EMF detection circuits.

The ESC must know or estimate the rotor position continuously to coordinate commutation accurately. This introduces two design paradigms: sensor-based and sensorless control.

**Sensor-Based ESC Operation**

In sensor-based systems, the ESC uses feedback from position sensors mounted on the motor shaft to determine the rotor's orientation. The most common type of sensor used is the Hall-effect sensor, which detects the magnetic field of the rotor magnets and outputs signals indicating their relative position.

A typical 3-phase BLDC motor with sensors includes three Hall sensors spaced 120 electrical degrees apart. As the rotor spins, the sensors produce a sequence of digital high/low signals representing the magnetic field's polarity at each point.

The ESC reads this signal pattern and determines which two of the three motor phases should be energized next. For example, if Hall sensors A, B, and C output sequence "101", the ESC might energize Phase A positively and Phase B negatively, leaving Phase C floating. After a known delay or upon the next signal change, it will switch to the next step in the six-step trapezoidal commutation sequence.

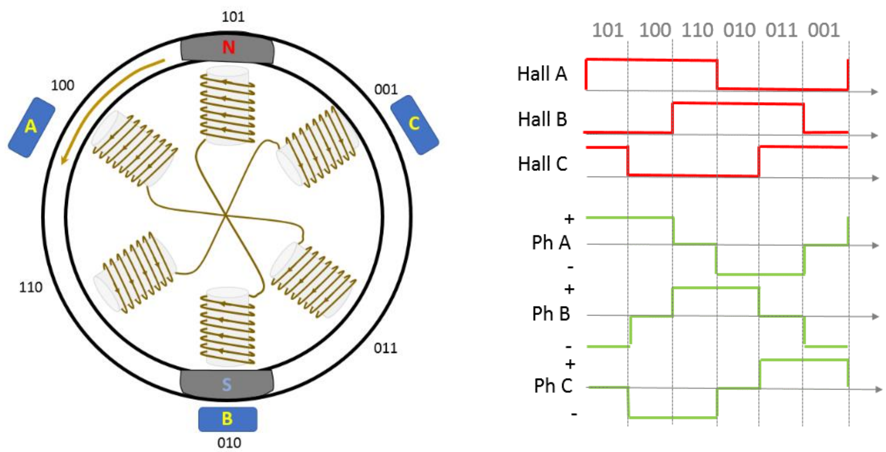

*Figure 17: HALL sensors signals*

**Sensorless ESC Operation**

In sensorless systems, the ESC has no physical rotor position sensors. Instead, it infers the position by analyzing the back electromotive force (back-EMF) generated in the unpowered phase of the motor.

When the rotor spins, it cuts through the magnetic field lines of the stator windings, inducing a voltage (back-EMF) that is proportional to the speed and magnetic field strength. This voltage has a predictable shape and phase relative to the rotor's position.

Back-EMF in a BLDC motor arises in accordance with Faraday's and Lenz's Laws, acting as a voltage that opposes the applied input and is directly proportional to both the rotational speed of the rotor and the rate of magnetic flux variation across the stator windings.

BLDC motor manufacturers specify a parameter known as the back-EMF constant, which can be used to estimate the voltage generated at a given speed. The voltage across a winding can be calculated by subtracting the back-EMF value from the supply voltage. Motors are typically designed so that at nominal speed, the voltage difference between the supply voltage and the back-EMF results in the motor drawing its rated current and delivering its rated torque.

When the motor operates above its rated speed, the back-EMF rises substantially, decreasing the voltage difference across the windings. This reduction leads to lower current flow and, consequently, a decrease in output torque. If the motor reaches a speed where the back-EMF matches the supply voltage, both current and torque will fall to zero. Since back-EMF opposes torque generation, it is often seen as a drawback. However, it can also be used to estimate the rotor's position.

The following figure shows a model of the motor windings, where $L_i$ represents the inductances, $R_i$ the winding resistances (typically a few ohms), and $e_i$ the back-EMF voltages.

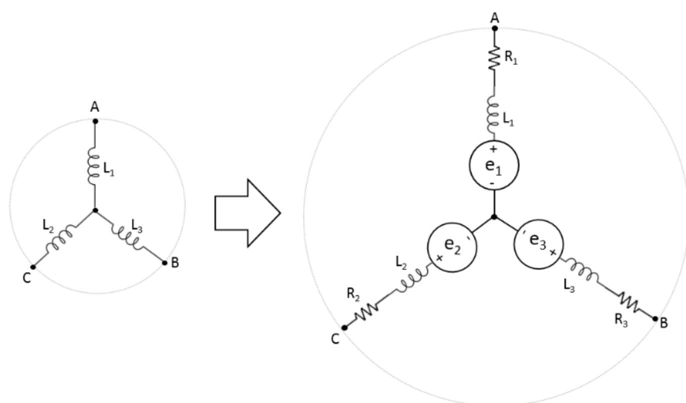


*Figure 18: Model of BLDC windings*

In a sensorless commutation, the ESC energizes two phases and leaves the third floating. It monitors the voltage on the floating phase and waits until the back-EMF signal crosses a reference point, typically half the DC bus voltage, known as the zero-crossing point.

Once this zero-crossing is detected, the ESC waits a calculated delay (commutation interval) before switching to the next phase combination. This delay accounts for the desired lead or lag angle needed for torque optimization.

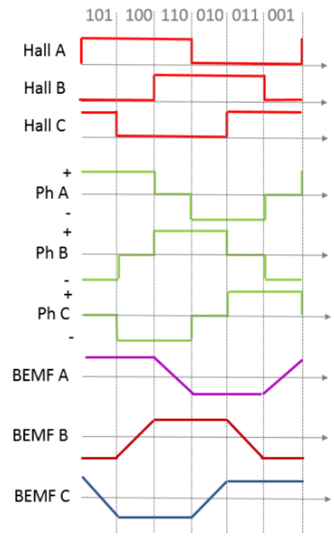

*Figure 19: BEMF signals compared to Hall sensors signals*

Figure 18 shows that one end of the voltage source $e_i$, specifically the terminal connected to the star point, is not directly accessible. As a result, an alternative method is required to accurately measure or estimate this voltage.

The most straightforward method entails comparing the back-EMF to half of the DC bus voltage using a comparator. The schematic below depicts this setup, where a comparator (or op-amp) is connected to each of the three windings, comparing their signals against a reference voltage equal to half of the DC bus voltage.

In the setup shown, winding A is positively energized, winding C is negatively (GND) energized, and winding B is left floating. As the commutation sequence progresses, the back-EMF on winding B rises and falls accordingly.

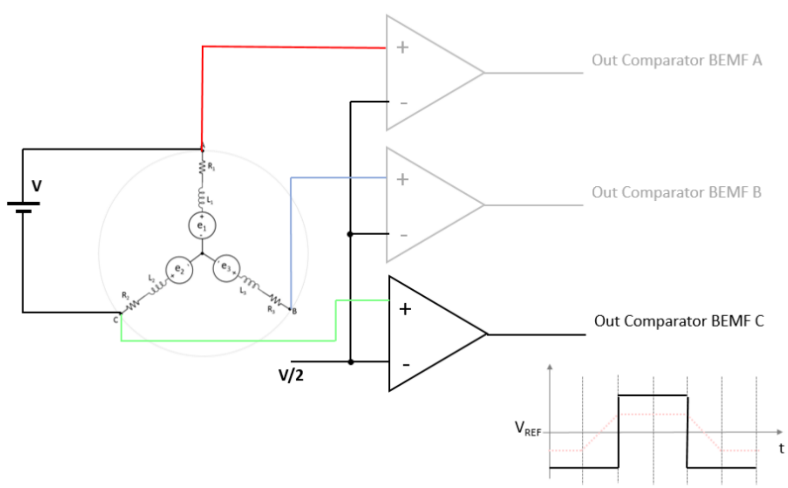

*Figure 20: Simple comparator circuit for measuring back-EMF*

The main limitation of this basic comparator method is that the three windings may not have perfectly identical electrical characteristics. This can lead to a positive or negative phase shift relative to the actual zero-crossing point of the back-EMF. While the motor will likely continue operating, it may draw excessive current, reducing efficiency and potentially increasing thermal stress.

A more accurate solution involves generating a virtual neutral point, as shown in the next figure. This is achieved by connecting three resistors in a star configuration, in parallel with the motor windings. The back-EMF of the floating phase is then compared to this virtual neutral voltage, improving the reliability of the zero-crossing detection.

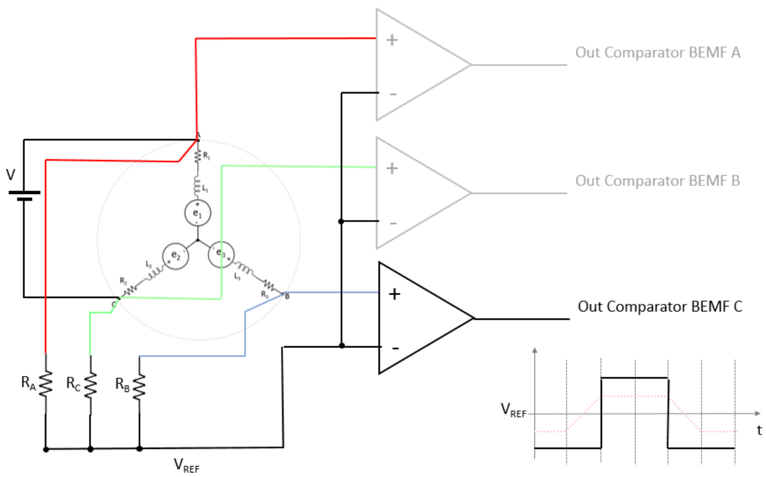

*Figure 21: Comparator circuit for measuring back-EMF with virtual reference*

One major limitation of sensor-less BLDC motor control is that no back-EMF is generated when the motor is stationary, leaving the MCU unable to determine the rotor's position. To overcome this, the motor is typically started in open-loop mode by energizing the windings in a predefined sequence, which initiates rotation, albeit with limited efficiency. Once the motor reaches a sufficient speed, the resulting back-EMF provides the necessary feedback for the system to transition to standard closed-loop operation, enabling precise and efficient control.

*Table 3: Sensor and sensorless based control comparison*

| Feature | Sensor based control | Sensor-less control |
|---|---|---|
| Rotor position detection | Via Hall sensors | Via back-EMF estimation |
| Startup performance | Excellent | Moderate to poor |
| Low-speed control | Very good | Weak or unstable |
| Cost and complexity | Higher | Lower |
| Reliability | Prone to sensor failure | More robust |
| Application areas | Robotics, automation | Drones, fans, e-skateboards |

A more advanced method leverages high-speed analog-to-digital converters (ADCs), which are commonly built into microcontrollers (MCUs) designed for BLDC motor control. In this approach, the ADC samples the back-EMF signal and compares it to a digital reference representing the zero-crossing point. This technique offers several benefits, for instance, it allows the application of digital filtering to suppress high-frequency switching noise, leading to cleaner signals and more precise zero-crossing detection.

## Conclusion

Brushless DC motors (BLDCs) have become a foundational technology in modern engineering, powering a wide range of applications from electric vehicles and robotics to drones and consumer electronics. Their high efficiency, compact size, and brushless architecture make them ideal for systems where precision, reliability, and performance are essential.

In this article, we have adopted a discursive and simple approach, aiming not only to describe the technical fundamentals of BLDC motors, but also to make the concepts understandable to students, enthusiasts, and engineers who may be encountering these systems for the first time. Complex topics, such as PWM control, zero-crossing detection, and Back-EMF behavior, were explained with real-world analogies, diagrams, and examples to build intuitive understanding alongside theoretical clarity.

**About the Author**

Leonardo Chieco is electronics engineer with more than 20 years of experience in software design and development for automation control (PC/PLC), electronic board design for industrial applications, firmware, robotics, and mechatronics.

Email: leochieco72@gmail.com

LinkedIn: https://www.linkedin.com/in/leonardo-chieco-53550b129/