TECHNICAL UNIVERSITY
OF CLUJ-NAPOCA
ROMANIA

ELECTRONIC SPEED CONTROLLERS FOR BLDC MOTORS

SEMESTER PROJECT

POWER ELECTRONICS

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1. DC Motors

An electric motor is a device that converts electrical energy into mechanical energy by utilizing electromagnetic phenomena. These motors operate through the interaction of conductors carrying current in a direction perpendicular to a magnetic field.

Electric motors come in several types, including AC (Alternating Current) and DC (Direct Current). AC motors are efficient and flexible, converting AC electrical energy into mechanical energy. They can be synchronous (with a constant speed) or asynchronous (with variable speed). DC motors, on the other hand, convert DC electrical energy into mechanical motion. They include brushed DC motors, brushless DC motors, and permanent magnet DC motors. Each type has specific applications based on efficiency, control, and precision requirements.

1.1. Working Principle:

A brushed DC motor operates based on electromagnetic induction. When a direct current (DC) flows through the armature windings, it interacts with the magnetic field of the stator (stationary part). This interaction causes the motor to rotate. The key components involved in this process are the commutator and the brushes.

1.2. Main Components:

Stator: The stator is the static part of the DC motor. It houses the field windings and receives the power supply.

Rotor (Armature): The rotor is the rotating part of the motor. It brings about mechanical rotations.

Yoke: The yoke is the magnetic frame surrounding the stator. It provides protection and support to the armature and field system.

Poles: The magnetic poles are structures attached to the inner wall of the yoke. They consist of a pole core and a pole shoe. The pole shoe spreads the flux produced over the air gap between the stator and rotor.

Field Windings: These are copper wire coils wound over the pole shoes. When field current flows through them, adjacent poles with opposite polarity are produced.

Armature Winding: The armature winding is attached to the rotor. It experiences an alternating magnetic field during rotation. The rotor core is made of low-hysteresis silicon steel laminations to reduce magnetic losses.

Commutator: The commutator is a segmented cylindrical structure connected to the rotor. It reverses the current direction in the armature windings as the rotor turns.

Brushes: Carbon or graphite brushes make sliding contact with the commutator. They relay the current from the external circuit to the rotating commutator, allowing continuous rotation12.

1.3. Control of a DC motor:

Voltage Control: Varying the voltage supplied to the motor allows control over its speed and torque. Lower voltage slows down the motor, while higher voltage speeds it up. Reversing the motor's direction is achieved by changing the polarity of the voltage.

Pulse Width Modulation (PWM): PWM is commonly used for speed control. It involves rapidly switching the motor's power supply on and off. Adjusting the duty cycle (percentage of time the power is on) controls the average voltage delivered to the motor. A higher duty cycle results in faster motor speed.

H-Bridge Circuit: For bidirectional control, an H-bridge circuit is used. It consists of four switches arranged in a bridge configuration. Selectively turning on/off the switches changes current flow direction through the motor. Widely used in applications like electric car windows and industrial servos.

Integrated Motor Control: Some motors integrate control features directly. Embedded gate drivers, power transistors, and protection functions are included. However, brushed motors have shorter lifetimes compared to brushless ones.

1.4. Equivalent circuit of a DC motor:

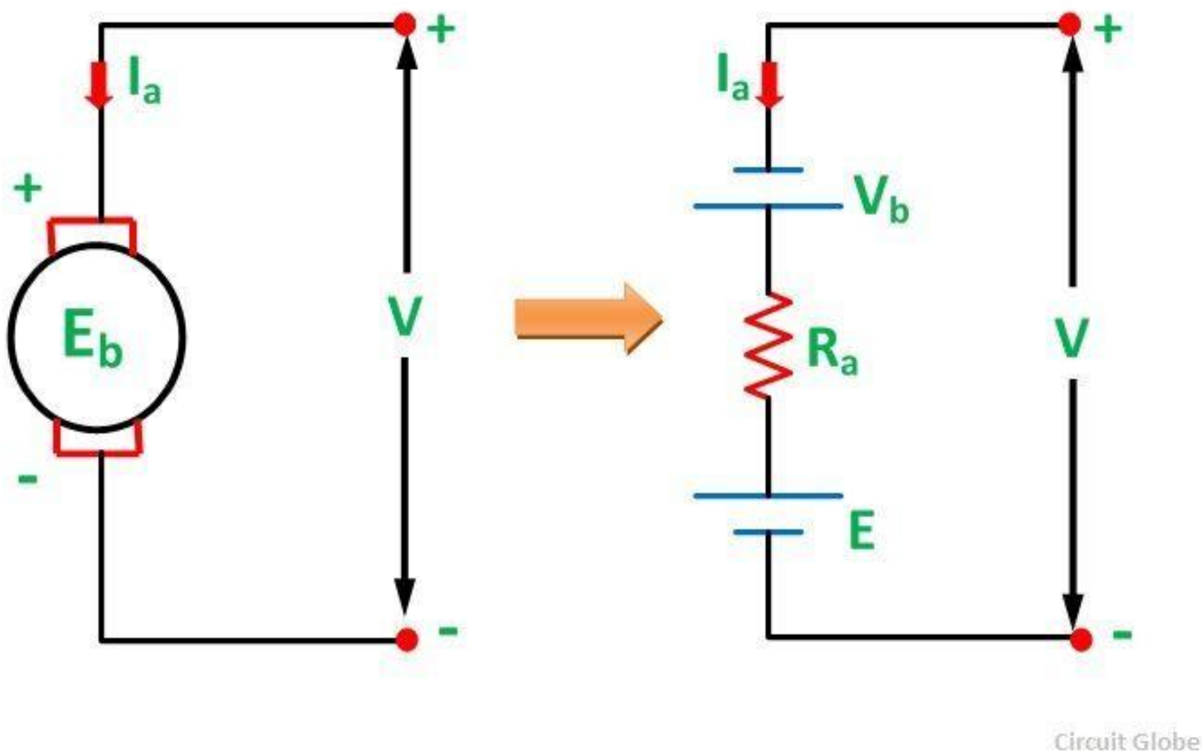

Figure 1

1.5. Modelling the brushed DC motor:

To understand the performance of practical DC machines, let us start with the elementary two-pole DC machine. The voltage equations for the field winding and rotor coil are essential for analysis:

Field voltage:

$$v_f = r_f \frac{di_f}{dt} + L_f \frac{di_a}{dt}$$

Armature voltage:

$$v_a = r_a i_a + L_a \frac{di_a}{dt}$$

The mutual inductance between the field winding and an armature coil is approximately:

$$L_{af} = L_{fa} = -L\cos{(\theta_r)}$$

where (L) is a constant.

Commutation occurs when the commutator switches the stationary terminals from one rotor coil terminal to the other. It is desirable to commute the rotor coil at the instant the induced voltage is at a minimum.

A more detailed model includes the back electromotive force (EMF), armature resistance, and other parameters. The symbolic and generic model captures the essential elements of a brushed DC motor for further analysis and control.

1.6. The block model of a DC motor:

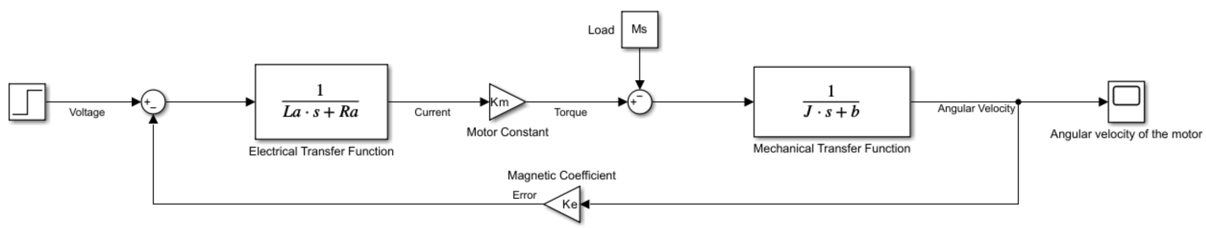

Figure 2

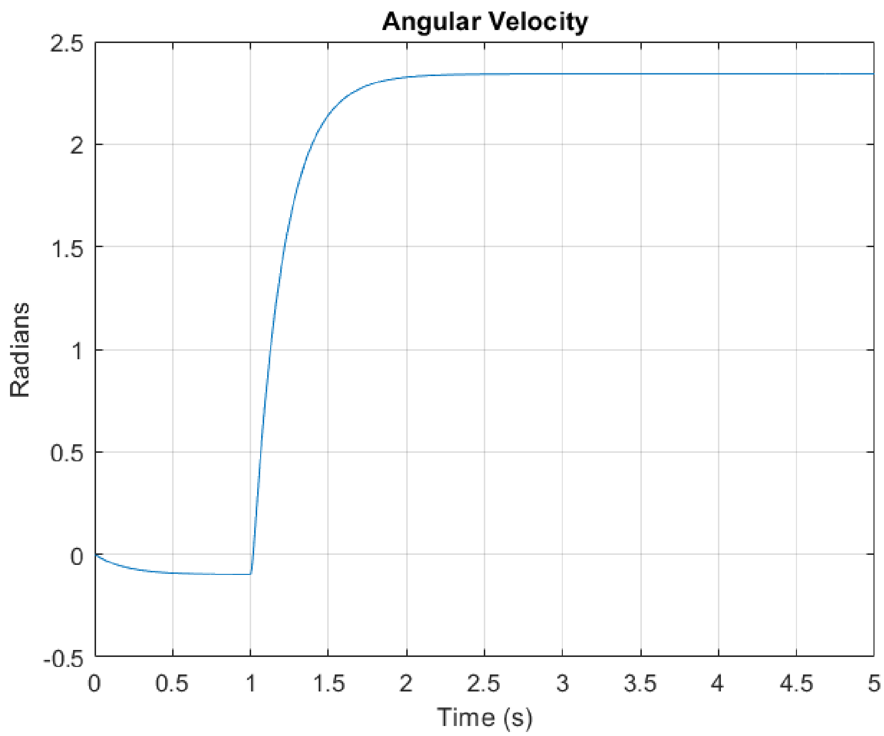

Figure 3

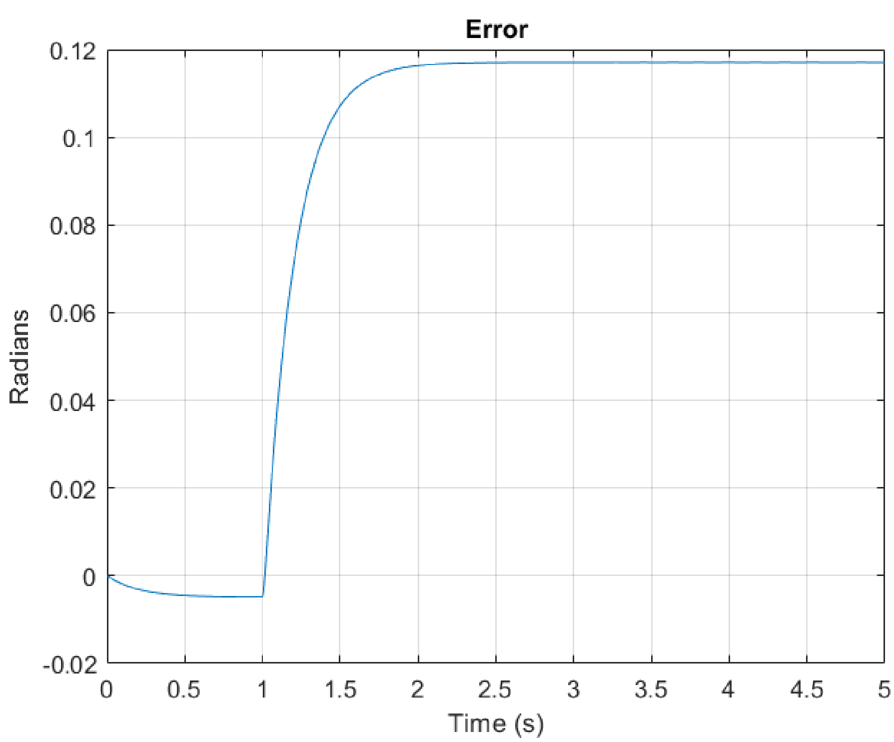

Figure 4

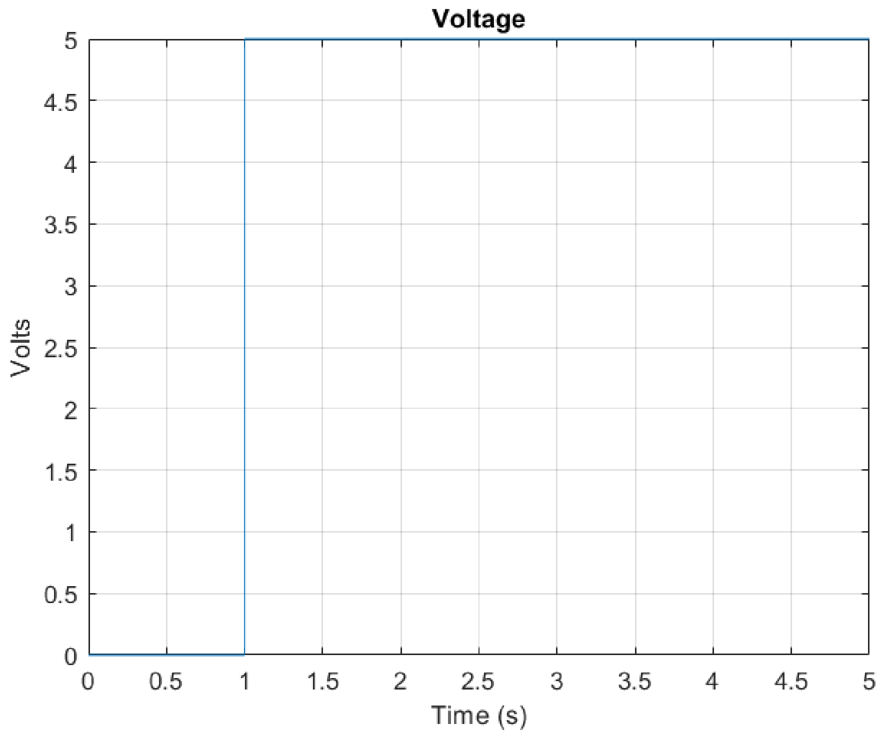

Figure 5

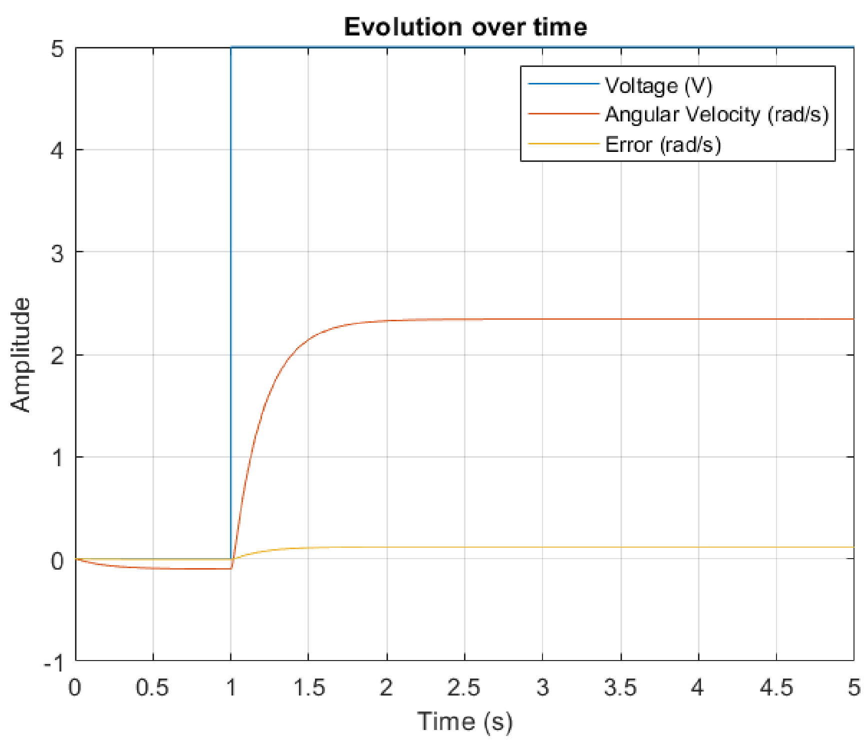

Figure 6

1.7. Disadvantages:

Limited Speed Range: DC motors have a restricted speed range. They can effectively operate only within a certain range of speeds. This limitation makes them less suitable for applications where variable speed control is critical.

Wear and Tear: Over time, DC motors can experience wear and tear. Frequent use or extended operation can lead to decreased performance or even motor failure. Repairing or replacing worn-out components can be costly.

Electromagnetic Interference (EMI): DC motors generate electromagnetic interference (EMI). This interference can disrupt the operation of other electronic devices in the vicinity. In applications where sensitive electronic equipment is used, EMI can be problematic.

High Initial Cost: The initial cost of DC motors can be relatively high compared to other motor types. This cost includes components like the commutator and brush gear.

Complex Control Circuits: While DC motors are easy to control at a basic level, more complex control requirements can lead to intricate control circuits. Achieving specific performance characteristics or advanced features may involve additional complexity.

Despite these disadvantages, DC motors still find applications in various fields due to their advantages, such as high efficiency, precise speed control, and minimal maintenance.

2. BLDC Motors:

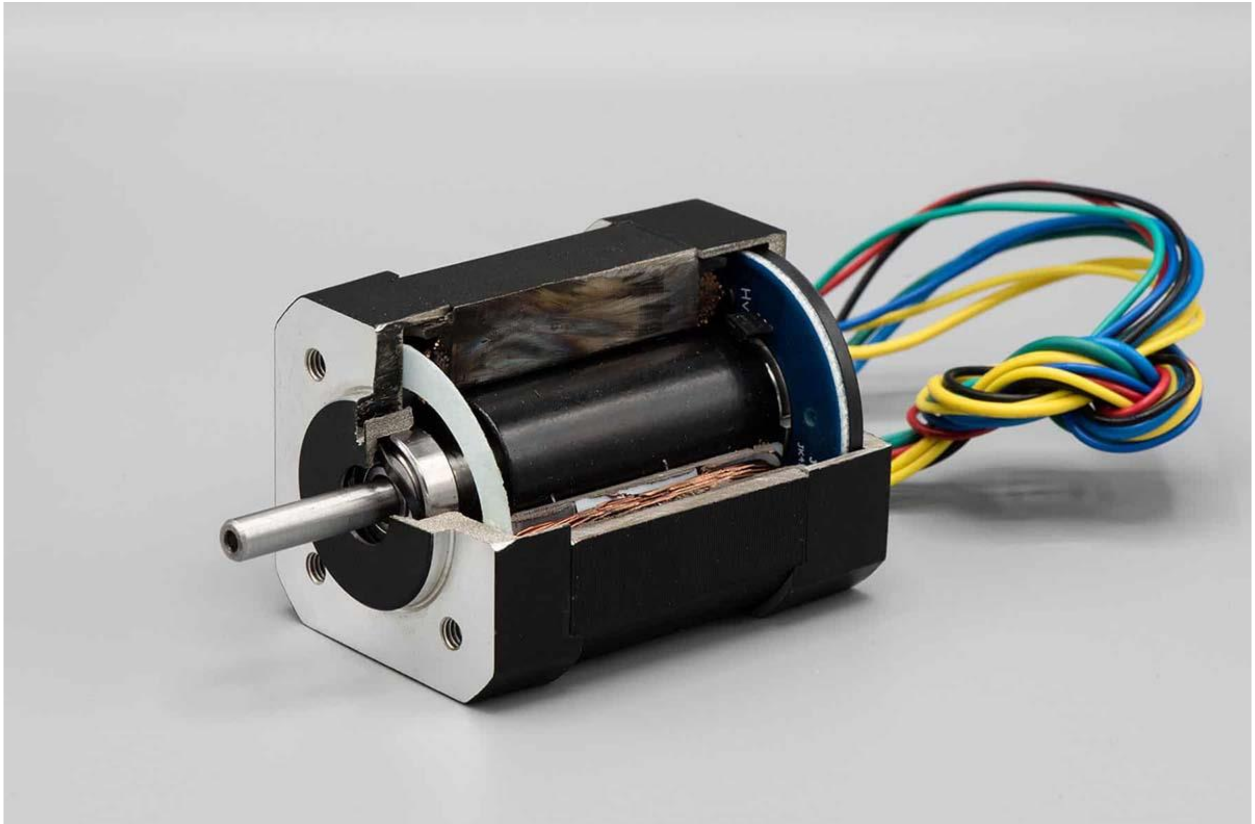

Figure 7

Brushed DC Motors have a simpler design, consisting of brushes and a commutator. The commutator mechanically switches the rotor windings, allowing the motor to operate. These motors are cost-effective and offer straightforward speed control. However, they suffer from wear due to brush friction, require periodic brush replacement, and are less efficient overall.

In contrast, Brushless DC Motors (BLDC) eliminate brushes and commutators entirely. Instead, they rely on electronic control to switch stator coils precisely. BLDC motors are highly efficient, maintenance-free (no brushes to replace), and have a longer operational life. However, they come with increased complexity, a higher price tag, and require specialized controllers. BLDC motors find applications in appliances, electric vehicles, robotics, and industrial automation.

2.1. Usage of BLDC motors:

Brushless DC motors (BLDC) find applications in various fields due to their efficiency, reliability, and versatility. Here are some notable areas where BLDC motors are commonly used:

Automotive Industry:

- **Electric Vehicles (EVs):** BLDC motors power electric cars, providing efficient and reliable propulsion. They offer high torque at low speeds, making them suitable for EVs.
- **Hybrid Vehicles:** BLDC motors are used in hybrid vehicles for functions like regenerative braking and electric power assistance.
- **Electric Bicycles (E-Bikes):** E-bikes utilize BLDC motors for pedal assistance and efficient energy conversion.

Industrial Automation:

- **Robotics:** BLDC motors drive robot joints, arms, and grippers. Their precise control and high torque-to-weight ratio make them ideal for robotic applications.
- **Conveyor Belts:** BLDC motors power conveyor systems in factories, warehouses, and logistics centers.
- **CNC Machines:** Computer Numerical Control (CNC) machines use BLDC motors for precise movement and positioning.

Home Appliances:

- **Air Conditioners and Refrigerators:** BLDC motors drive fans and compressors in air conditioners and refrigerators, ensuring efficient cooling.
- **Washing Machines:** BLDC motors enable direct-drive designs, eliminating the need for belts and gearboxes.
- **Electric Fans:** BLDC motors provide quiet operation and fine-grained fan power adjustment.

Consumer Electronics:

- **Hard Drives:** BLDC motors rotate hard disk drives (HDDs) in PCs, laptops, and servers.
- **DVD/CD Players:** BLDC motors spin optical discs in DVD and CD players.
- **Blu-Ray Recorders:** BLDC motors are used in Blu-Ray drives.

Healthcare Equipment:

- **Medical Devices:** BLDC motors are found in medical equipment such as infusion pumps, ventilators, and centrifuges.
- **Dental Tools:** BLDC motors drive dental drills and other precision instruments.

Aviation and Aerospace:

- **Drones and UAVs:** BLDC motors power propellers and gimbals in unmanned aerial vehicles (drones).
- **Satellites and Spacecraft:** BLDC motors are used in satellite mechanisms and scientific instruments.

Computer Peripherals:

- **Printers:** BLDC motors drive paper feed mechanisms in laser printers.
- **Scanners:** Scanners use BLDC motors for precise movement.
- **Optical Drives:** BLDC motors spin CDs, DVDs, and Blu-Ray discs.

Power Tools:

- **Cordless Drills:** BLDC motors provide high torque and longer battery life.
- **Circular Saws:** BLDC motors drive saw blades efficiently.
- **Grinders and Sanders:** BLDC motors power various handheld tools.

2.2. Advantages of a BLDC motor:

Brushless DC (BLDC) motors offer several advantages over traditional brushed motors:

- **High Efficiency:** BLDC motors are known for their high efficiency, converting electrical energy into mechanical energy with minimal losses. This makes them ideal for applications where energy efficiency is crucial, such as electric vehicles and renewable energy systems1.
- **Longer Lifespan:** BLDC motors have a longer operational life compared to brushed motors. The absence of brushes reduces wear and tear, leading to increased durability and reliability.
- **Less Maintenance:** Since BLDC motors do not have brushes, they require less maintenance. There is no need for periodic brush replacement, making them suitable for long-term use.
- **Greater Power, Torque, and Speed:** BLDC motors provide greater power, higher torque, and faster speeds compared to their brushed counterparts. This performance advantage is essential in various applications.
- **Precision and Control:** BLDC motors can provide higher levels of precision and control. Their smooth operation, absence of brushes, and electronic control make them suitable for applications requiring accuracy.
- **Reduced Noise and Vibration:** BLDC motors produce less noise and vibration, making them beneficial in environments where quiet operation is essential.
- **Lightweight and Compact:** BLDC motors are lightweight and compact, making them well-suited for portable devices, robotics, and other space-constrained applications.

2.3. Rotation of a BLDC motor:

A BLDC motor consists of two primary parts:

- **Rotor:** The rotor is the rotating part of the motor. It contains permanent magnets.
- **Stator:** The stator is the stationary part of the motor. It houses stator windings (coils).

The key to BLDC motor operation lies in the interaction between the rotor's permanent magnets and the stator's windings. When an electric current flows through the stator windings, they generate a magnetic field. The permanent magnets on the rotor interact with this magnetic field, resulting in torque that causes the rotor to rotate. The direction of rotation is controlled by changing the direction of the magnetic fields generated by the stator coils.

BLDC motors use electronic commutation instead of mechanical brushes. The controller provides pulses of current to the motor windings. These pulses determine the speed and torque of the synchronous motor. The controller activates specific stator windings at precise moments to create a rotating magnetic field. As the rotor's permanent magnets encounter this changing magnetic field, they experience torque, causing the rotor to spin. The controller continuously adjusts the current to maintain the desired speed and direction.

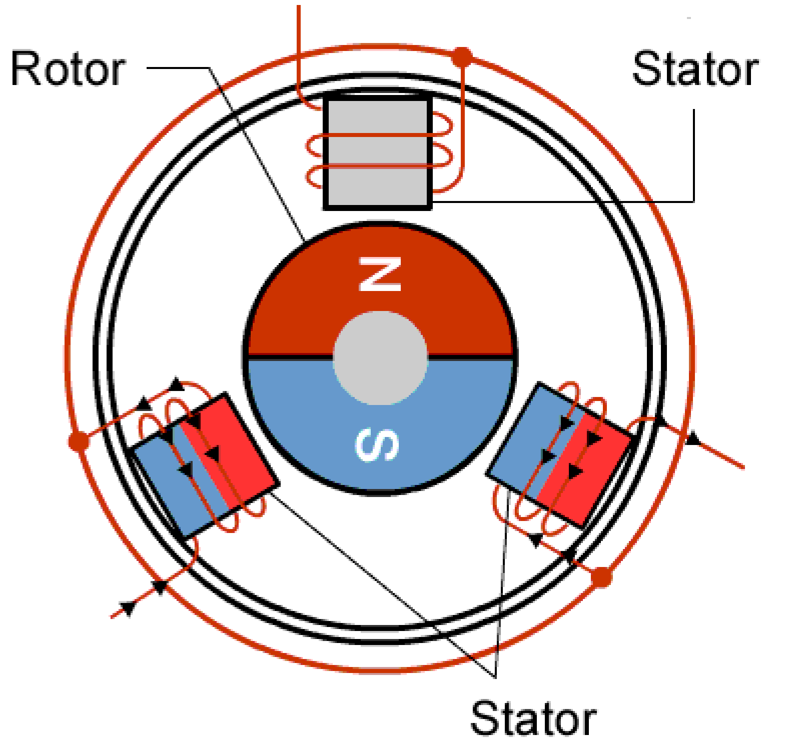

Figure 8

2.4. Main parts of a BLDC motor:

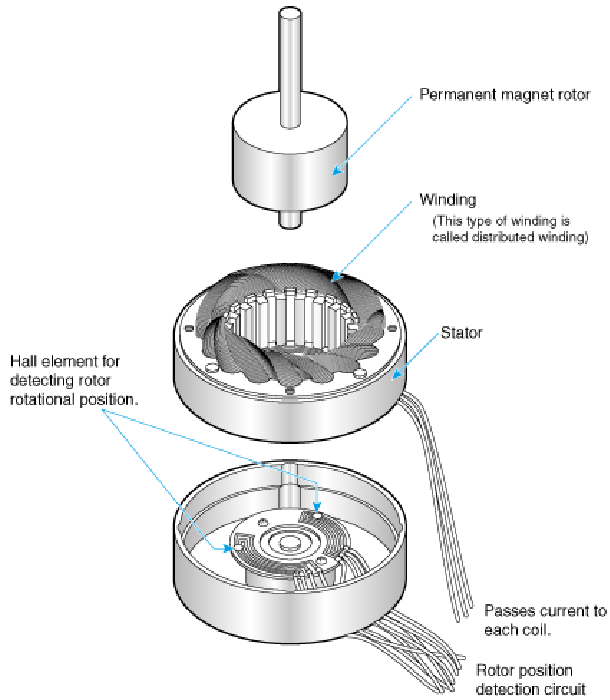

Figure 9

A Brushless DC (BLDC) motor consists of two main parts: the stator and the rotor.

The stator is the stationary part of the BLDC motor. It contains permanent magnets arranged in a circular pattern. The stator windings (coils) are wound around the stator core. These windings create a magnetic field when current flows through them. The stator's primary function is to generate a rotating magnetic field that interacts with the rotor.

The rotor is the rotating part of the motor. It typically consists of a permanent magnet with two poles (north and south). The rotor is mounted on a shaft and positioned inside the stator. As the stator's magnetic field changes due to the energized coils, it interacts with the rotor's permanent magnet, causing the rotor to rotate. The rotor's movement generates mechanical output (rotation) that can be harnessed for various applications.

2.5. Inrunner & outrunner BLDC motors:

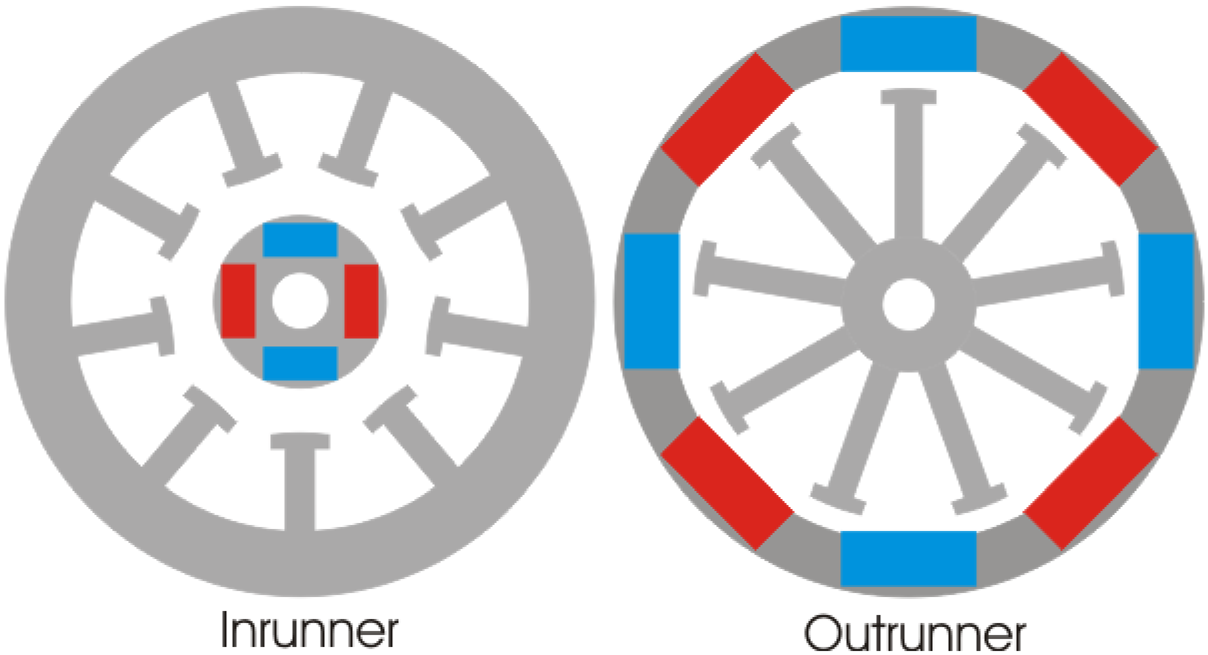

Figure 10

In inrunner motors, the rotor (armature) is positioned inside the stator. The stator windings surround the rotor. Due to the rotor being inside the stator, inrunners offer relatively low accuracy. They exhibit higher efficiency compared to outrunners because of their lower inertia and they generate lower torque. Inrunners are smaller in overall size and have a smaller diameter, but they are axially longer, achieving higher RPM per volt for motors of identical size. Heat dissipation is efficient since the magnets are inside the winding.

Inrunners are commonly used in applications requiring high speed, such as electric ducted fan (EDF) jets, cars, and trucks. They require relatively high maintenance.

Outrunners have the rotor positioned outside the stator. Magnets are attached to the rotor, which rotates around the fixed stator windings. The external rotor design provides relatively high accuracy. Outrunners have lower efficiency due to their higher inertia and they generate higher torque.

These type of BLDC motors are larger overall and have a larger diameter, but they are shorter axially. achieving lower RPM per volt for motors of identical size. Their RPM is limited due to the need for more magnets at higher voltages. Heat transfers to the center of the motor, primarily through the shaft.

Outrunners excel in applications requiring high torque, such as 3D airplanes, warbirds, trainer planes, helicopters, and drones. They require relatively minimal maintenance.

2.6. Input of a BLDC Motors, speed, and torque control:

The speed of a BLDC motor can be controlled by adjusting the input DC voltage or current. Higher voltage results in higher speed. Two primary methods for speed control are:

- **Open Loop Speed Control:** Involves simply chopping the DC voltage applied to the motor terminals. However, this method may result in some form of current limiting.
- **Closed Loop Speed Control:** Utilizes feedback from the motor to control the input supply voltage. The supply voltage is adjusted based on the error signal (difference between desired and actual speed).

Components:

- **PWM circuit:** Generates PWM pulses (can be a microcontroller or a timer IC).
- **Sensing device:** Measures the actual motor speed (e.g., hall effect sensor, infrared sensor, or optical encoder).

BLDC motors achieve torque control by varying the voltage applied to the motor windings. The commutation of power transistors energizes specific windings in the stator to provide optimum torque generation based on the rotor position. The effective voltage (proportional to the PWM duty cycle) controls both the motor speed and available torque.

Trapezoidal Commutation is one of the simplest methods. Current is controlled through motor terminals one pair at a time. Three Hall devices are embedded in the motor providing digital signals to measure rotor position within 60-degree sectors. The motor controller then switches (commutates) the current every 60 degrees of rotation. This method produces current space vectors with six different directions.

2.7. Equivalent circuit

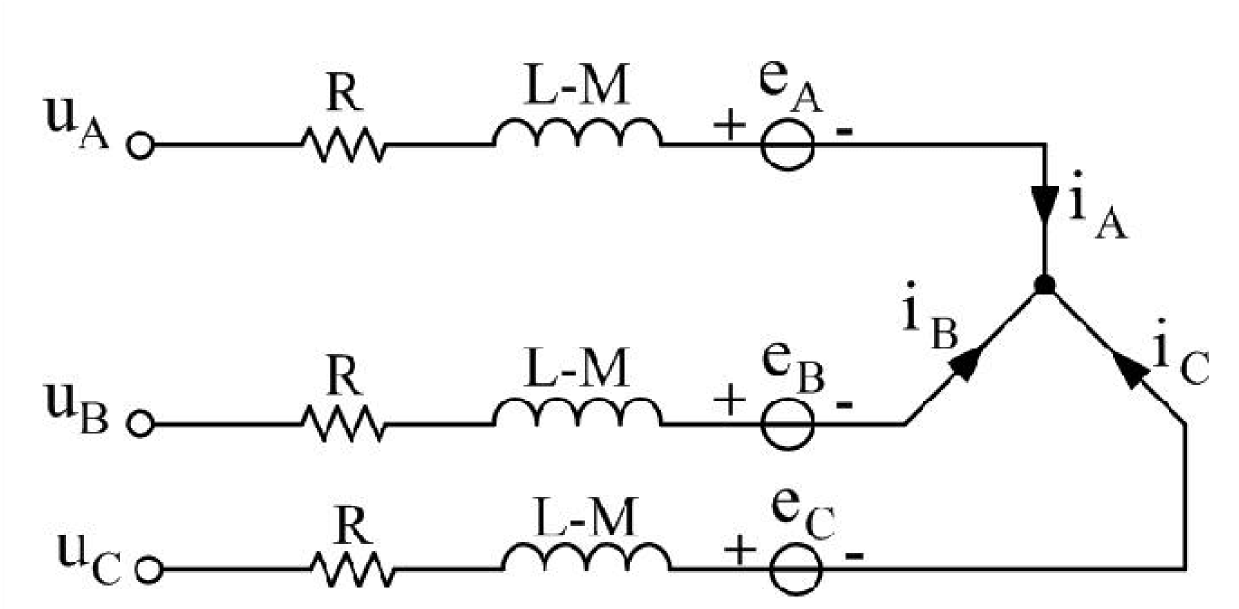

Figure 11

2.8. Model of a BLDC motor

The dynamic equations for a p-pole, 3-phase BLDC motor are derived using space vectors. These equations account for both electrical and mechanical effects. The motor's behavior is often modeled in a three-axis system, known as the d-q coordinate system.

The following components contribute to the dynamic equations:

- **Stator Currents:** The phase currents (ia(t), ib(t), ic(t) satisfy the equation:
$$i_a(t) + i_b(t) + i_c(t) = 0.$$
- **Stator Fluxes:** The fluxes (λas(θ, t), λbs(θ,t), λcs(θ,t)) are related to the stator currents and inductances. This relationship can be generally expressed as:

$$\lambda_{a_s}(\theta, t) = L_{a_s}(\theta) \cdot i_a(t),$$

$$\lambda_{b_s}(\theta, t) = L_{b_s}(\theta) \cdot i_b(t),$$

$$\lambda_{c_s}(\theta, t) = L_{c_s}(\theta) \cdot i_c(t),$$

- **Back-EMF (e_emf):** The back-EMF voltage is calculated based on the rate of change of flux.

$$e_{emf} = -\frac{d\lambda}{dt}.$$

- **Stator Voltages:** The stator voltages (vas(t), vbs(t), vcs(t)) are influenced by the stator resistance (R_s) and the back-EMF.

$$v_{a_s}(t) = R_s \cdot i_a(t) + e_{emf},$$

$$v_{b_s}(t) = R_s \cdot i_b(t) + e_{emf},$$

$$v_{c_s}(t) = R_s \cdot i_c(t) + e_{emf}.$$

- **Flux Magnitude:** The flux magnitude produced by permanent magnets (λ_pm) is assumed sinusoidally distributed in the airgap.

$$\lambda_{pm}(\theta, t) = \lambda_{pm0} \cdot \cos(\theta - \omega t).$$

Accurate rotor position sensing is crucial for BLDC motor control. Various methods, such as Hall sensors or encoder feedback, are used to determine the rotor position.

In our scenario, we first determine the system's Transfer function. This allows us to shape our PI controller accordingly. I performed an identification process on the existing signal, which led to the modeling of the PI controller. The transfer function that emerged from this process was then used as the controller, following the computation of a suitable regulator.

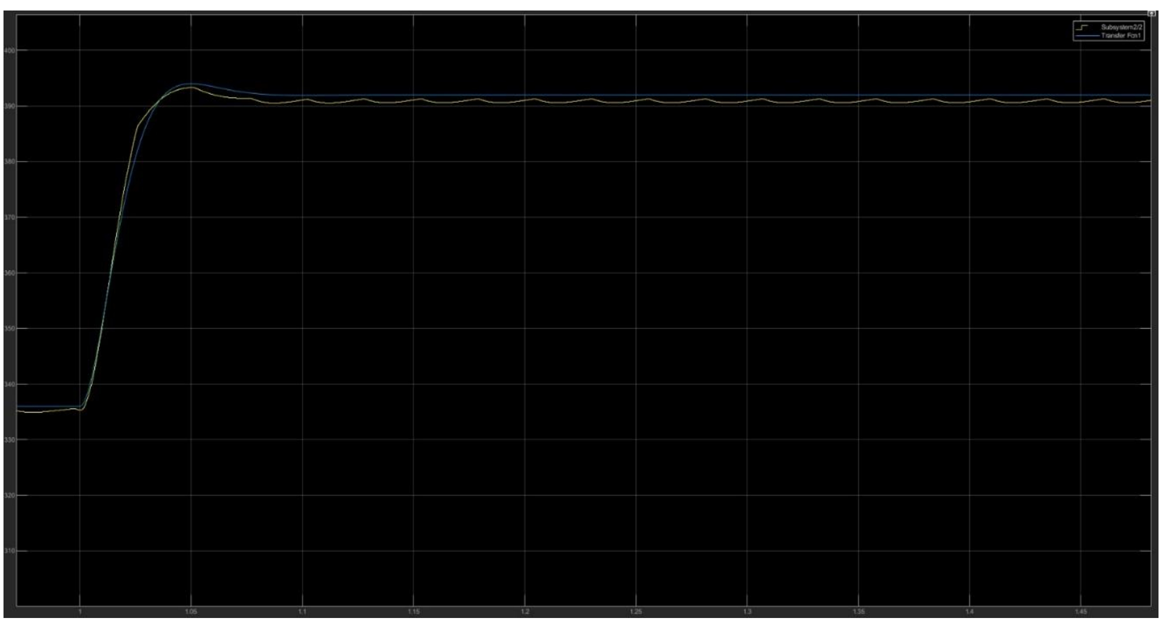

Figure 12

3. Inverters

BLDC motors (or brushless DC motors) are indeed powered from DC sources. However, they use a style of inverter to convert this DC power into a waveform that switches to activate the motor windings as required.

The inverter for a BLDC motor is designed specifically for the motor itself. It converts the DC input into a waveform that switches the motor windings effectively, allowing precise control over the motor's operation.

3.1. What is a PWM signal?

PWM is a technique where the duty cycle of a square wave is varied to control the average voltage or current delivered to a load. In the context of BLDC motors, PWM is used to control the power supplied to the motor windings.

The basic idea is to switch the power on and off rapidly (at a high frequency) while adjusting the ratio of on-time (duty cycle) to off-time. By varying the duty cycle, the effective voltage across the motor coils can be adjusted, allowing precise control of motor speed and torque.

3.2. BLDC Motor Control with PWM:

BLDC motors typically have three phases (U, V, and W). The inverter circuit (often called the motor controller) generates a three-phase PWM signals. Each phase is driven by a pair of transistors (usually MOSFETs or IGBTs) that switch on and off rapidly. The PWM signals control the timing and duration of these switching events.

By adjusting the duty cycle of each phase, the inverter can regulate the effective voltage applied to the motor windings. The motor responds by rotating at a speed proportional to the applied voltage and the load conditions.

3.3. Benefits of PWM in BLDC Motors:

Speed Control: PWM allows precise speed control by adjusting the duty cycle. Higher duty cycles result in higher average voltage and faster motor rotation.

Torque Control: By varying the duty cycle, the motor's torque output can be controlled.

Efficiency: PWM minimizes power losses in the motor and reduces heat generation.

Smooth Operation: The rapid switching of PWM minimizes motor vibration and noise.

Regenerative Braking: In some applications, PWM can be used for regenerative braking, where energy is fed back into the power supply during deceleration.

4. Electronic speed controller (ESC)

An Electronic Speed Controller (ESC) is a crucial component in the control system of Brushless DC (BLDC) motors. The ESC is responsible for controlling the speed and direction of the BLDC motor. It converts DC power from a battery into a three-phase AC signal to drive the motor.

The ESC uses a control algorithm to determine the optimal timing and sequence for energizing the motor phases. The most common control algorithms are trapezoidal and sinusoidal, and they dictate how the current is applied to the motor windings.

Some ESCs are sensor less, relying on back-emf (electromotive force) to determine the rotor position. Others use Hall effect sensors for more precise position feedback. Sensor less ESCs infer the rotor position based on the voltage induced in the unpowered motor phases.

The ESCs control the motor speed by adjusting the duty cycle of a high-frequency PWM signal. The duty cycle determines the average voltage applied to the motor, affecting its speed.

5. Inner control loop

The inner control loop in a BLDC motor control system is typically responsible for controlling and adjusting the motor current. This is often implemented using a variety of control strategies, such as Proportional-Integral (PI) control, sliding mode control, or others.

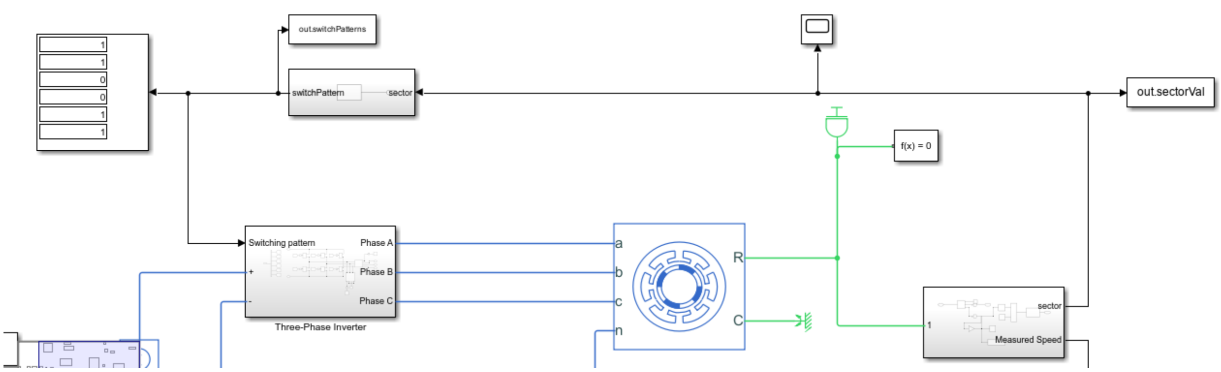

Figure 13

The purpose of the inner control loop is to quickly respond to changes in the motor current, which is related to the motor torque. By accurately controlling the motor current, the inner control loop can help to control the motor torque, thereby improving the performance of the motor.

The inner control loop is often part of a larger control system, which may include an outer control loop for speed or position control. The outer loop provides a reference to the inner loop, which then works to control the motor current to achieve this reference.

In some cases, the inner control loop may also include additional features, such as current limiting, to protect the motor and power electronics from damage.

6. Outer control loop

The outer control loop in a BLDC motor control system is typically responsible for controlling the speed or position of the motor. This is often implemented using a variety of control strategies, such as Proportional-Integral-Derivative (PID) control, model predictive control, or others.

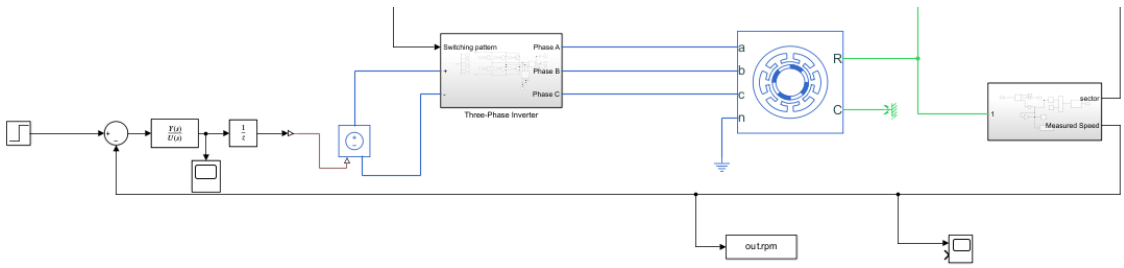

Figure 14

The purpose of the outer control loop is to respond to changes in the motor speed or position, which are higher-level objectives compared to the motor current controlled by the inner loop. By accurately controlling the motor speed or position, the outer control loop can help to achieve the desired performance of the motor.

The outer control loop provides a reference to the inner control loop, which then works to control the motor current to achieve this reference. In this way, the outer and inner control loops work together to control the motor.

In some cases, the outer control loop may also include additional features, such as speed limiting or position limiting, to protect the motor and the system from damage.

In our situation, the outer loop incorporates the PI controller we had previously established. This configuration enables us to manipulate the motor's velocity as needed.

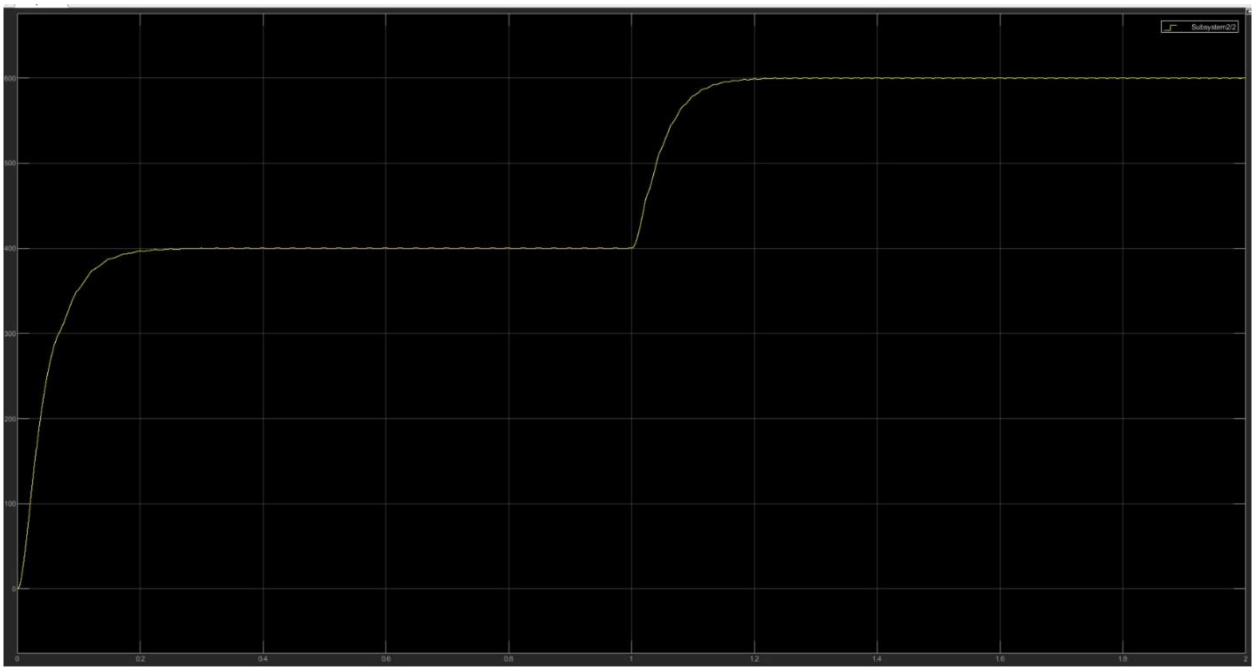

Figure 15

7. Controlling the motor speed with PWM signal via Buck converter

In a Brushless DC (BLDC) motor control system, the speed of the motor is often controlled using a Pulse Width Modulation (PWM) signal via a Buck converter. The PWM signal adjusts a constant DC voltage to different voltage levels, which helps control the motor at varying speeds.

A Buck converter is a DC-to-DC power converter that steps down voltage from its input (source) to its output (load). It does this by storing energy in an inductor and then releasing it to the load at a different voltage.

In the context of motor speed control, a Buck converter can be used along with a PWM generator to step down the DC source voltage to the three-phase inverter. The speed of a BLDC motor is proportional to the supply voltage, so varying the motor voltage is commonly called 'speed control' even though it does not actually set the speed directly.

The control system typically involves two common architectures for PWM control. In the first one, the Buck converter along with a PWM generator is used to step down the DC source voltage to the three-phase inverter.

8. Controlling the motor speed with PWM on the three phase voltages

Controlling the speed of a Brushless DC (BLDC) motor using Pulse Width Modulation (PWM) on the three-phase voltages is a common approach in motor control.

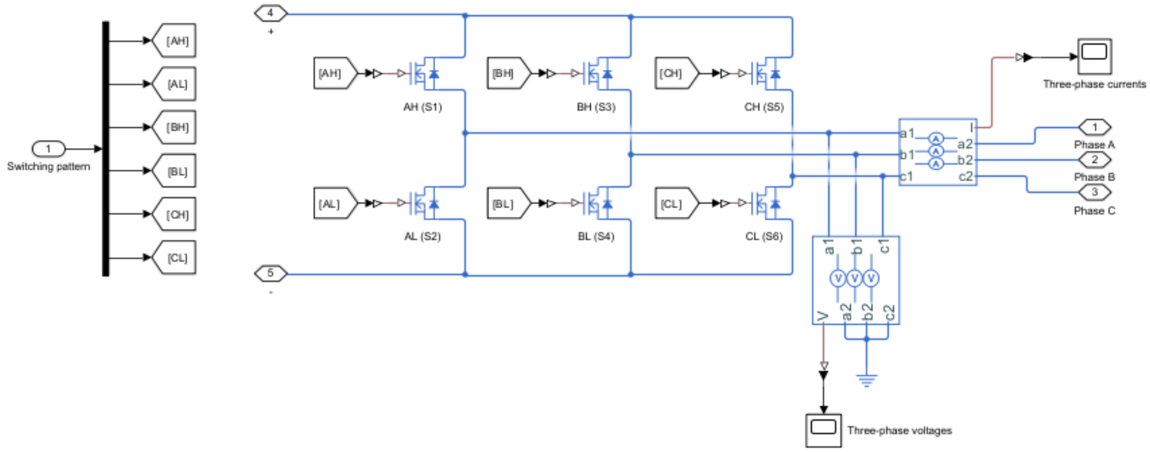

Figure 16

The PWM signal adjusts the duty cycle of the voltage applied to the motor, effectively controlling the average voltage supplied to the motor1. This average voltage is proportional to the speed of the motor, so by adjusting the PWM signal, you can control the speed of the motor.

In a three-phase BLDC motor, there are three PWM signals corresponding to the three phases of the motor. These PWM signals are typically generated by a microcontroller or other digital control system.

The PWM signals are then used to control a three-phase inverter, which converts the DC power supply into three-phase AC power for the motor. By adjusting the PWM signals, the inverter can control the voltage and frequency of the three-phase power, thereby controlling the speed of the motor.