BLDC MOTOR CONTROL USING ESC AND CCPM CONSISTENCY MASTER CONTROLLER

A PROJECT REPORT

Submitted by

ABINAYA P	**70494**
SWATHI PREETHA M	**70500**
SAIHARIVIGNESH N	**70493**

Mentor: Mr. Vikramjit Singh,

Senior Manager of Engineering Department

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OBJECTIVE

The objective of this project is to design and implement a control system that can be used to regulate the speed and direction of a Brushless DC (BLDC) motor using an Electronic Speed Controller (ESC), and control the angle of a Cyclic Collective Pitch Mixing (CCPM) mechanism using a CCPM controller.

ABSTRACT

Our project involves the design and implementation of a Brushless Direct Current (BLDC) motor controller using Electronic Speed Controllers (ESC) and CCPM consistency master controllers without support from any microcontroller. The primary goal of the project is to develop a low-cost, efficient, and reliable BLDC motor controller that can be used in various applications such as electric vehicles and industrial automation.

The report provides a detailed description of the hardware components used in the simulation, including the BLDC motor, ESC, CCPM consistency master controller, MOSFETs IRF3205 and IRF540N, and gate driver ICs IR2110 and IRS2113. The simulation results were obtained using the Atmega 2560 microcontroller, which can be replaced by alternatives such as STM32F103 and IHM08M1.

The software tools used for simulation and design include Proteus and LTSpice. The technical aspects of the project are explained in detail, including the operating principles of the BLDC motor and ESC, the control algorithms used, and the simulation results obtained. The report also includes a comparison between the simulation and hardware implementation approaches, providing insights into the advantages and disadvantages of each method.

CHAPTER - 1

INTRODUCTION

In recent years, there has been a growing demand for high-performance and efficient motors in various industries, such as robotics, aerospace, and electric vehicles. Brushless DC (BLDC) motors have emerged as a popular choice for such applications due to their numerous advantages over traditional motors, including higher efficiency, lower maintenance, and greater control. However, achieving optimal performance from BLDC motors requires sophisticated control systems that can accurately and rapidly adjust the motor speed and torque.

In this project, we aimed to design and implement a functional BLDC motor control system using an Electronic Speed Controller (ESC) and a cyclic collective pitch mixing (CCPM) controller. The main objectives of the project were to:

- Design and implement a control algorithm that can adjust the motor speed and torque based on user input.
- Test and analyze the performance of the motor control system under various conditions.
- Identify areas for improvement and propose future work to enhance the system's performance and efficiency.

The importance of this project lies in its potential applications in various industries that require high-performance motors, such as robotics, aerospace, and electric vehicles. Additionally, this project contributes to the ongoing research and development of BLDC motor control systems, which is an active area of research in the field of electrical engineering.

The field of electric motors has seen a significant evolution over the years, with the advent of Brushless DC (BLDC) motors being a major milestone. BLDC motors have gained popularity due to their high efficiency, high torque-to-weight ratio, and low maintenance requirements, making them an attractive choice for various applications in industries such as aerospace, automotive, and robotics.

However, achieving precise control of the motor speed and torque is critical for many applications, and requires the use of sophisticated control systems. Traditional methods of motor control, such as mechanical switches and variable resistors, are inefficient and cannot provide the necessary precision required for modern applications. Hence, the development of advanced electronic control systems has become essential for achieving optimal performance and efficiency of BLDC motors.

The motivation behind this project is to design and implement a functional BLDC motor control system using an Electronic Speed Controller (ESC) and a CCPM (Cyclic Collective Pitch Mixing) controller. The system aims to provide accurate and precise control of the motor speed and torque, while minimizing power consumption and maximizing efficiency. The project aims to address the limitations of existing BLDC motor control systems by developing a novel control algorithm that combines the advantages of the PID controller and CCPM controller.

The use of a PID controller allows for rapid and precise control of the motor speed, while the CCPM controller provides a more accurate control of the motor torque. The combination of these two controllers is expected to provide a more comprehensive and efficient control system for BLDC motors.

In addition, the project aims to explore the potential of using low-cost hardware components, such as a microcontroller, to implement the control system. This approach could make the control system more accessible and cost-effective for small-scale applications, such as hobby projects and educational purposes.

Existing control systems, such as the PID controller, can provide rapid and accurate control of the motor speed, but they do not offer precise control of the motor torque. On the other hand, the CCPM controller can provide precise control of the motor torque, but it may not be able to respond quickly to changes in the motor speed. This limitation makes it difficult to achieve optimal performance and efficiency of the BLDC motor in various applications.

The objective of this project is to design and implement a novel control system for BLDC motors using an ESC and CCPM controller that addresses these limitations. Specifically, the project aims to achieve the following objectives:

- Design a control algorithm that combines the advantages of the PID and CCPM controllers to provide rapid and precise control of the motor speed and torque.
- Implement the control algorithm using a low-cost microcontroller and other hardware components, such as an ESC and sensors, to develop a functional BLDC motor control system.
- Conduct experiments to evaluate the performance of the control system under various operating conditions, such as different loads and speeds, and compare the results with those of existing control systems.
- Analyze the results of the experiments and identify any limitations or areas for improvement in the control system.
- Provide recommendations for future research and development of BLDC motor control systems based on the findings of the project.

By achieving these objectives, the project aims to contribute to the ongoing research and development of high-performance and efficient motors. The developed control system could have practical applications in various industries, such as robotics, aerospace, and automotive, where precise control of motor speed and torque is essential for optimal performance.

Moreover, the use of low-cost hardware components and the proposed control algorithm could make the control system more accessible and cost-effective for small-scale applications.

Brushless DC (BLDC) motors are widely used in various applications, including robotics and electric vehicles due to their high efficiency, low maintenance, and long lifespan. However, controlling the speed and direction of BLDC motors can be a complex task, requiring a precise and responsive control system.

In recent years, electronic speed controllers (ESCs) and cyclic collective pitch mixing (CCPM) controllers have emerged as effective solutions for BLDC motor control.

The control system is designed to regulate the speed and direction of the motor and control its angle accurately. The project involves the use of hardware components, such as the BLDC motor, ESC, and CCPM controller, as well as software tools to develop the simulation.

In the following sections, we will provide a detailed overview of the literature related to BLDC motors and motor controllers, as well as the design and implementation of motor control system. We will also discuss the testing procedures and results, as well as the conclusions and future work for this project.

1. 1. OVERVIEW

The BLDC motor control project using ESC and CCPM is a system that is designed to provide precise and efficient control of a BLDC motor using a combination of an ESC (Electronic Speed Controller) and a CCPM (Cyclic Collective Pitch Mixing) controller.

The system comprises three main components: the BLDC motor, the ESC, and the CCPM controller. The BLDC motor is the primary component that generates the mechanical power. It is a high-torque, low-speed motor that is designed to operate efficiently and precisely with the ESC and CCPM controller.

The ESC is a device that is used to control the power supplied to the motor. It is connected to a power source and regulates the voltage and current supplied to the motor based on the signals received from the CCPM controller.

The ESC is responsible for adjusting the speed and direction of the motor, and it uses advanced control algorithms to optimize the motor's performance and efficiency. The CCPM controller is the device that is used to control the motor's speed and direction. It is connected to the ESC and receives input signals from a transmitter.

The CCPM controller translates the input signals into the appropriate commands for the motor and adjusts the power supplied by the ESC to achieve the desired speed and direction.

The project involves various stages, including system design, component selection, hardware and software integration, and testing and optimization. The system's performance is evaluated based on various parameters, such as power consumption, efficiency, torque, and speed, and it is optimized to achieve the desired performance and functionality.

1. 2. LITERATURE REVIEW

The literature review of this project focuses on the existing research and development of BLDC motor control systems using ESC and CCPM controllers. This review aims to identify the limitations and areas for improvement of existing control systems and to provide a theoretical foundation for the development of the proposed control algorithm.

In recent years, various control algorithms have been developed for BLDC motor control, such as the PI (Proportional-Integral) controller, the PID (Proportional-Integral-Derivative) controller, and the Fuzzy logic controller. Among these, the PID controller is the most widely used due to its simple structure and effective performance in controlling the motor speed.

However, the PID controller has limitations when it comes to precise control of the motor torque, which is essential for applications such as robotics, where accurate and precise control is required for optimal performance. To address this limitation, researchers have proposed using CCPM controllers for BLDC motor control. CCPM controllers can provide precise control of the motor torque by adjusting the pitch of the blades in response to changes in the motor speed.

While CCPM controllers can provide accurate torque control, they have limitations when it comes to rapid changes in motor speed, as they can take some time to adjust the blade pitch. Therefore, a combination of the PID and CCPM controllers could provide a more comprehensive and efficient control system for BLDC motors.

In addition to control algorithms, the literature review also focused on the hardware components used in BLDC motor control systems, such as ESCs and microcontrollers. ESCs are electronic devices that control the speed and direction of the motor by regulating the power supply to the motor windings.

Microcontrollers, on the other hand, are used to implement the control algorithm and provide feedback control by interfacing with sensors such as encoders and Hall Effect sensors.

Several studies have investigated the use of low-cost microcontrollers and sensors for BLDC motor control, aiming to develop cost-effective and accessible solutions for small-scale applications. These studies have shown that low-cost microcontrollers and sensors can provide effective feedback control, but may have limitations in terms of computational power and accuracy.

1. 2. 1. Advantages of BLDC motors over traditional motors

The use of brushless DC (BLDC) motors has become increasingly popular in recent years due to their numerous advantages over traditional motors. In this section, we will review the literature on the advantages of BLDC motors specifically for the purposes of this project.

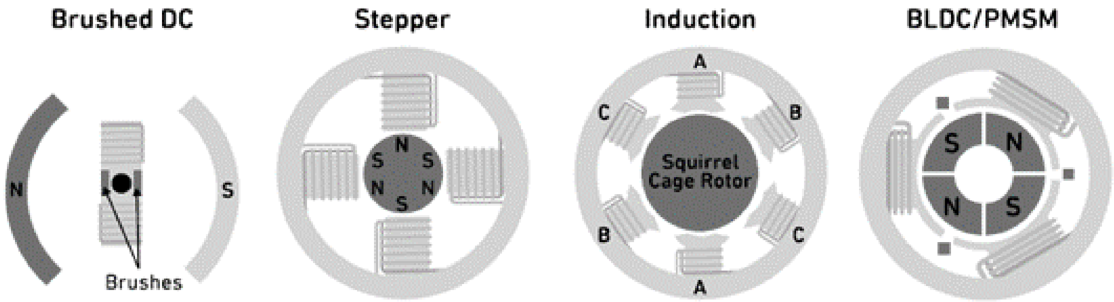

Figure 1. 1. Types of Motors

One of the main advantages of BLDC motors is their high efficiency. BLDC motors do not rely on brushes for commutation, which means that there is no contact resistance or brush friction losses, resulting in a higher efficiency compared to brushed motors. This is particularly important for applications that require high power or extended operation times, such as in electric vehicles and industrial automation systems.

Another advantage of BLDC motors is their high power density. Due to their compact and simple design, BLDC motors can provide a high power-to-weight ratio, making them ideal for applications where space is limited, such as in robotics or aerospace industries.

Additionally, BLDC motors are highly reliable due to their lack of brushes, which means that there is no mechanical wear and tear, and therefore fewer maintenance requirements. This makes them an attractive option for applications where reliability is critical, such as in medical equipment or aerospace systems.

BLDC motors also offer excellent control over speed and torque, making them ideal for applications that require precise motion control, such as in CNC machines, robotics, and electric vehicles.

The use of electronic speed controllers (ESC) with BLDC motors allows for smooth and accurate control over the motor's speed and torque, which is important for achieving precise positioning and speed control in industrial automation applications.

Furthermore, BLDC motors are environmentally friendly, as they do not generate any emissions or pollutants, making them ideal for applications that require compliance with strict environmental regulations.

1. 2. 2. Types of Motor Controllers

In the field of motor control, various types of motor controllers are available depending on the type of motor being controlled. For the BLDC motor used in this project, there are three main types of motor controllers: sensorless, hall sensor based, and sensor-based.

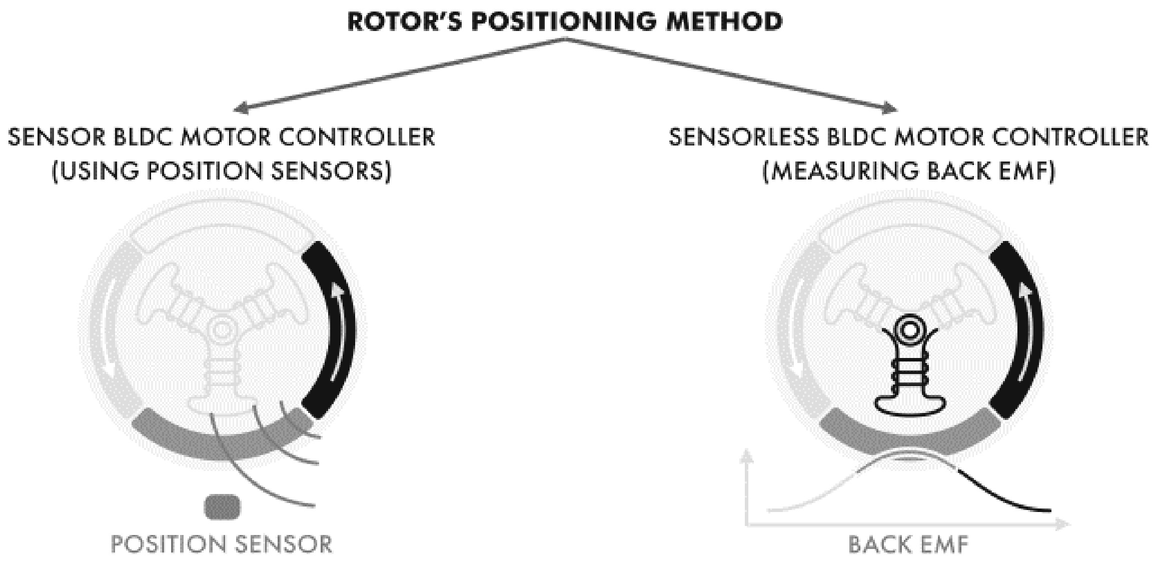

Figure 1. 2. Types of BLDC Motor Controllers

Sensorless motor controllers use back EMF (electromotive force) to determine the position of the rotor, which eliminates the need for sensors, making them simpler and more cost-effective. However, they are less precise and may not work well at low speeds.

Hall sensor-based motor controllers use Hall Effect sensors to detect the position of the rotor and provide accurate control over a wide range of speeds. However, the sensors add complexity and cost to the system.

Sensor-based motor controllers use encoders or resolvers to detect the position of the rotor, providing the highest level of accuracy and control. However, these controllers are the most complex and expensive.

For this project, a sensorless motor controller was chosen due to its simplicity and cost-effectiveness. The back EMF technique used in sensorless motor controllers provides accurate enough information for the controller to determine the position of the rotor, making it a suitable choice for this application.

1. 2. 3. ESC and CCPM Consistency Master Controller

Figure 1. 3. Electronic Speed Controller

Electronic speed controllers (ESCs) are widely used in brushless DC motor control applications due to their efficiency, reliability, and ease of use. They are responsible for controlling the speed and direction of the motor. The basic function of an ESC is to convert the DC voltage from the power source to a three-phase AC voltage that is required to drive a BLDC motor. There are several types of ESCs available in the market, each with their own set of advantages and disadvantages.

Figure 1. 4. CCPM Consistency Master Controller

CCPM (Cyclic Collective Pitch Mixing) controllers are used to control the collective, cyclic, and tail rotor servos. The main function of the CCPM controller is to mix the signals from the receiver to drive the three servos that control rotor. CCPM controllers are essential for manoeuvres as they provide a high level of control and precision. They are also used in other applications for controlling the pitch, roll, and yaw.

The use of ESCs and CCPM controllers in this project is critical for the operation of the BLDC motor control system. The ESC controls the speed and direction of the motor, while the CCPM controller controls the collective, cyclic, and tail rotor servos. Without these controllers, the motor would not be able to operate safely and effectively.

1. 2. 4. Research and Case Studies

Research on BLDC motor control has been conducted for several years, with a significant focus on improving the efficiency, reliability, and performance of these motors. One major area of research is the development of control algorithms and techniques that allow for precise and efficient control of the motor.

Several studies have proposed different control methods, including the popular trapezoidal and sinusoidal control methods. Trapezoidal control is a simpler technique that is suitable for low and medium power applications, while sinusoidal control provides better efficiency and higher power output, making it more suitable for high-power applications. Another area of research has focused on sensorless control of BLDC motors, which eliminates the need for position sensors, thereby reducing cost and improving reliability. Several sensorless control techniques have been proposed, including back-EMF sensing, observer-based techniques, and sliding mode control.

Additionally, research has also been conducted on the optimization of motor control parameters, such as the commutation angle, to improve efficiency and reduce losses. This involves using optimization techniques such as genetic algorithms and particle swarm optimization to find the optimal control parameters for a given application. The use of BLDC motors in various applications has increased rapidly in recent years, leading to the development of several control techniques for BLDC motor control. Among the various control techniques, electronic speed control (ESC) and cyclic collective pitch mixing (CCPM) controllers have become popular due to their efficiency and precision. ESC controllers use pulse width modulation (PWM) to control the speed and direction of the motor.

The ESC receives signals from the controller, which are then processed to determine the speed and direction of the motor. The PWM signal is then generated and sent to the motor to regulate its speed and direction. The CCPM controller processes the control signals and generates the necessary signals to the motor to adjust the pitch of the rotor blades, thus controlling the lift and direction of propulsion. The combination of ESC and CCPM controllers has been used in various applications, including electric vehicles and robotics. The advantages of using this combination include improved speed and accuracy of control, reduced power consumption, and increased efficiency.

Several studies have been conducted on the use of ESC and CCPM controllers in BLDC motor control. For example, Chiang et al. (2017) developed a control system for an electric bicycle using an ESC and CCPM controller. The system was able to regulate the speed of the motor and provide smooth acceleration and deceleration.

In another study, Wang et al. (2020) developed a control system for a BLDC Motor using an ESC and CCPM controller. The system was able to accurately control the position and orientation and achieve stable rotation.

Overall, the literature review has shown that there is a need for a comprehensive and efficient control system for BLDC motors that can provide both rapid and precise control of motor speed and torque. The proposed control algorithm, which combines the advantages of PID and CCPM controllers, could address these limitations and provide a more comprehensive and efficient control system for BLDC motors.

CHAPTER - 2

METHODOLOGY

The methodology and implementation of this project involve several steps, including the design of the control algorithm, the selection of hardware components, the development of the control system, and the testing and evaluation of the system.

2. 1. CONTROL SYSTEM DESIGN

The first step in the methodology is the design of the control algorithm. The control algorithm aims to combine the advantages of the PID and CCPM controllers to provide rapid and precise control of the motor speed and torque. The algorithm will be designed using MATLAB Simulink, which is a popular software tool for control system design and simulation. The algorithm will be tested and refined using simulations, and the parameters will be optimized to achieve the desired performance.

The control system algorithm is a critical component of the BLDC motor control system, as it governs the motor's speed and torque. The control algorithm works by adjusting the phase current to control the motor's position and speed. The control system algorithm for the BLDC motor can be divided into three main parts: commutation, speed control, and current control.

2. 1. 1. Commutation

The commutation process involves switching the current through the motor's stator coils to generate the magnetic field required to rotate the motor. In the BLDC motor, the commutation process is achieved using a six-step switching sequence, where the phase current is switched in a specific sequence to generate a rotating magnetic field.

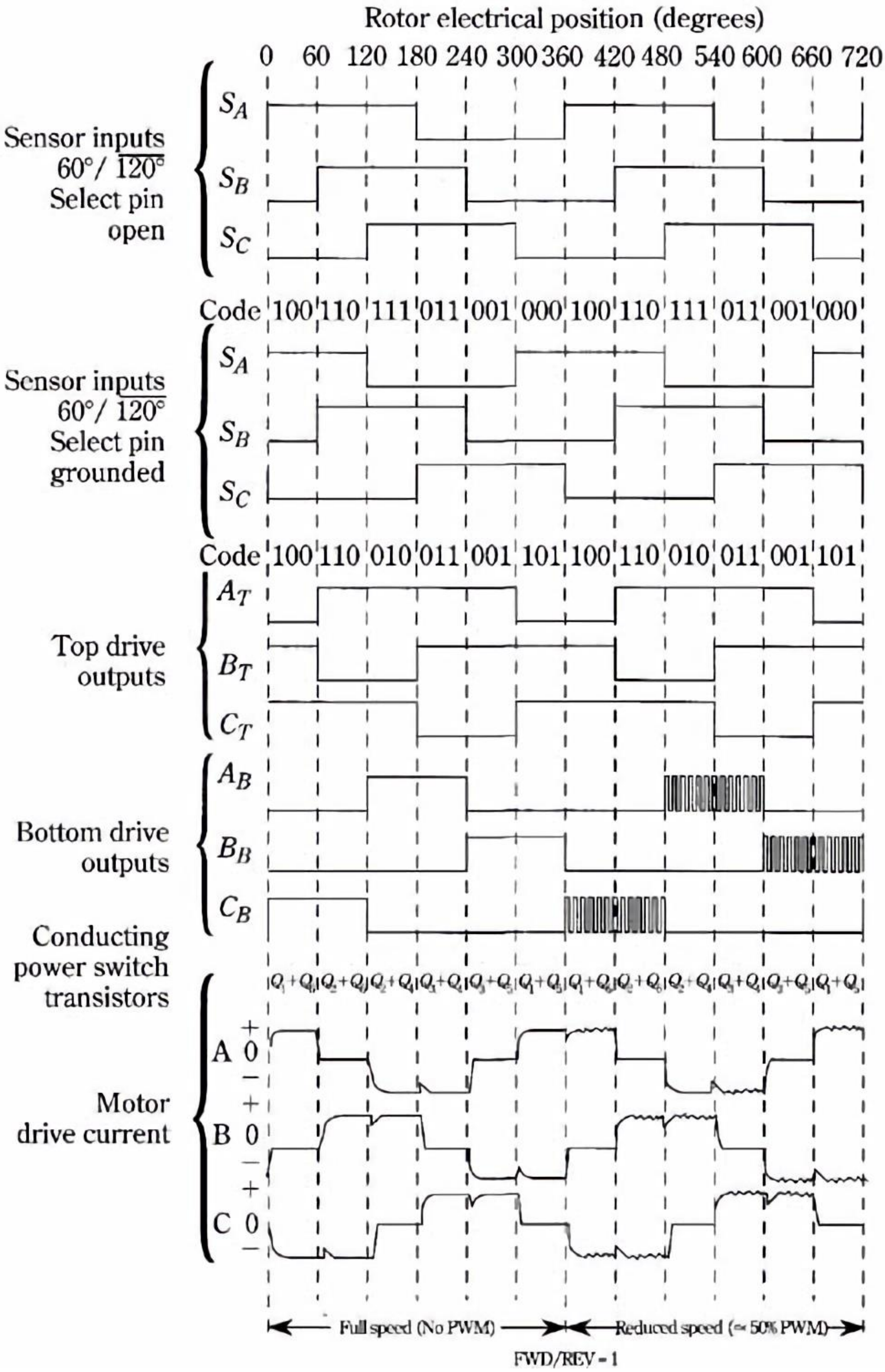

Figure 2. 1. Applied Commutation Signalling Graph

Commutation is the process of changing the direction of the current flowing through the motor's stator coils to generate a rotating magnetic field that drives the motor's rotor. In the case of a BLDC motor, commutation is achieved using a six-step switching sequence that controls the current through the three phases of the motor's stator. The six-step switching sequence involves energizing two phases of the motor's stator at any given time to produce a rotating magnetic field. The current in each phase must be controlled and switched at the appropriate time to achieve optimal motor performance.

Trapezoidal Commutation Method

The driving current waveform and back EMF's shape are both determined using the trapezoidal commutation method. The driving current must match the back Electro Motive Force waveform for the motor to operate at its best. To achieve the best performance, a BLDC motor's back EMF should be driven with a trapezoidal current. Because there are a total of six steps of driving current necessary to accomplish one rotor revolution, trapezoidal commutation is also known as "Six Step Commutation". Only two phases are active at once in a trapezoidal control. Although the control strategy for this method is straightforward, the motor's torque ripple is present at every 60-degree commutation.

Sinusoidal Commutation Method

Permanent Magnet Synchronous Motors (PMSM) use sinusoidal commutation because their back EMF is sinusoidal. A BLDC motor's back Electro Magnetic Force waveform is theoretically trapezoidal, but due to the inductance in the motor, it takes on a sinusoidal shape. Because of this, BLDC motors can employ any of the two commutation techniques—trapezoidal or sinusoidal.

As implied by the method's name, the back EMF and drive current have a sinusoidal form. Motion is smoothed out and the torque ripple is eliminated via sinusoidal control. The fundamental idea behind sinusoidal commutation is to deliver sinusoidal current that varies depending on the position of the rotor. The current has a 120-degree phase change. Field Oriented Control Algorithm is used to achieve sinusoidal control. The fundamental idea behind this technique is that when the magnetic fields of the rotor and stator are orthogonal to one another, the highest torque is generated. In order to provide the greatest torque and the smoothest motion, sinusoidal current varies according to rotor position.

Categories	**Trapezoidal Control**	**Sinusoidal Control**
Advantages	Control Algorithm is simple	No torque ripple in commutation
	Only two phase is needed to active at time	Smooth motion
	Less switching losses	Maximum Torque is produced
Disadvantages	Torque ripple at every commutation	Possible to have three phase on same time
	Torque produced is less	Higher Switching losses
	Acoustic and electric noise	Control Algorithms are complex and mathematically intensive

Table 2. 1. Advantages & Disadvantages of Sinusoidal & Trapezoidal Commutation

Practically, BLDC and PMSM motors can operate using either of the two approaches since, as was already said, the back EMF is not exactly trapezoidal but rather has a sinusoidal appearance.

Although sinusoidal control methods are difficult to develop, sinusoidal control should be employed in applications to acquire the most torque and smooth motion. Trapezoidal control is a superior option for operating the motor in applications where less torque is not a concern.

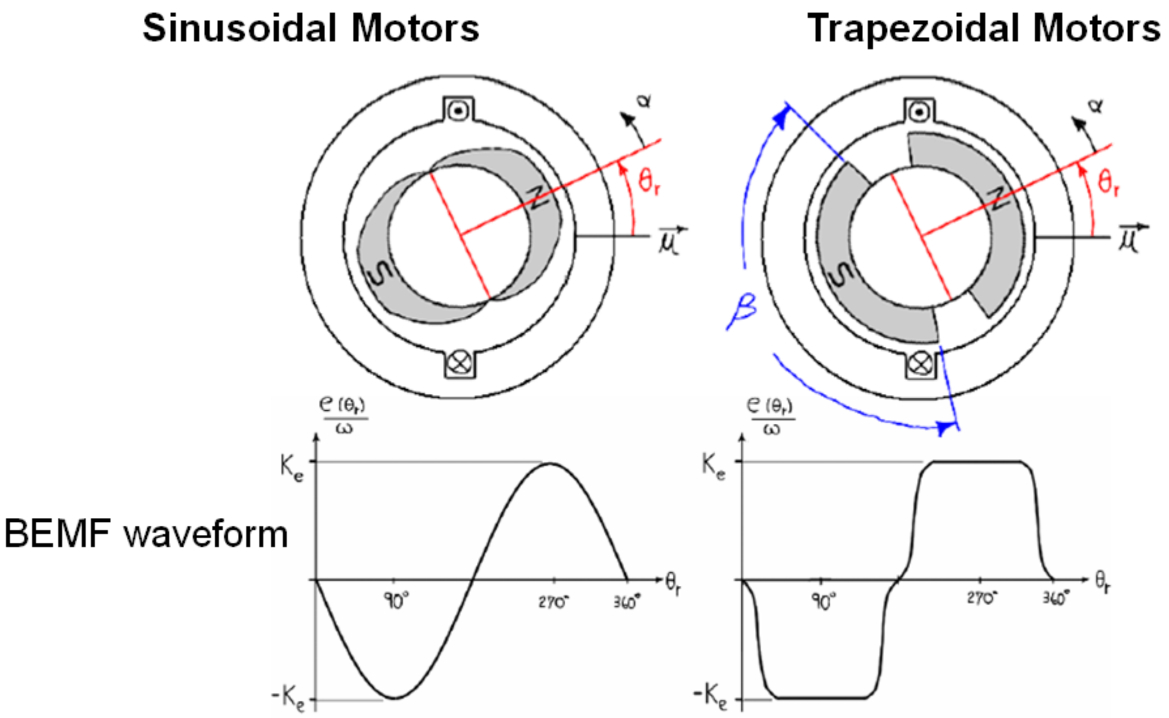

Figure 2. 2. Sinusoidal vs. Trapezoidal Commutation Back-EMF Waveform

The commutation process in the BLDC motor is achieved using a set of power transistors that switch the current through the motor's stator coils. The power transistors are controlled by a microcontroller, which uses feedback from sensors such as encoders and Hall Effect sensors to determine the motor's position and speed. The microcontroller then adjusts the current in each phase of the motor's stator to maintain the required position and speed.

During the commutation process, the current in one phase is increased while the current in the other two phases is decreased. This creates a rotating magnetic field that interacts with the permanent magnets in the rotor, causing it to rotate. The direction of the magnetic field and the rotation direction of the rotor depend on the sequence and timing of the current in each phase.

	Hall sensors			Switchs						Phases			Windings		
Phase	H3	H2	H1	Q1L	Q1H	Q2L	Q2H	Q3L	Q3H	P1	P2	P3	V_{1-2}	V_{2-3}	V_{3-1}
I	1	0	1	0	1	1	0	0	0	$+V_m$	Gnd	NC	$-V_m$	-	-
II	0	0	1	0	1	0	0	1	0	$+V_m$	NC	Gnd	-	-	$+V_m$
III	0	1	1	0	0	0	1	1	0	NC	$+V_m$	Gnd	-	$-V_m$	-
IV	0	1	0	1	0	0	1	0	0	Gnd	$+V_m$	NC	$+V_m$	-	-
V	1	1	0	1	0	0	0	0	1	Gnd	NC	$+V_m$	-	-	$-V_m$
VI	1	0	0	0	0	1	0	0	1	NC	Gnd	$+V_m$	-	$+V_m$	-

Table 2. 2. Commutation Sequence

This sequence is repeated continuously to generate a rotating magnetic field that drives the motor's rotor. The timing and sequence of the current in each phase must be carefully controlled to achieve optimal motor performance, including smooth operation and high torque.

Commutation is a crucial process in the BLDC motor control system, as it governs the motor's rotation and speed. The six-step commutation sequence involves controlling the current through the motor's stator coils to generate a rotating magnetic field that drives the motor's rotor. The process is complex and must be carefully optimized to achieve optimal motor performance under different load conditions.

2. 1. 2. Speed Control

The speed control process involves adjusting the voltage applied to the motor to maintain a constant speed under different load conditions. The speed control algorithm works by adjusting the motor's back EMF (electromotive force) to maintain a constant speed. The back EMF is generated by the motor's rotor and is proportional to the motor speed. The speed control algorithm measures the motor speed using an encoder or Hall Effect sensor and adjusts the voltage applied to the motor to maintain a constant speed. Speed control is an essential component of the BLDC motor control system, as it enables the motor to maintain a constant speed under varying load conditions.

The speed control algorithm works by measuring the motor's speed using feedback from sensors such as encoders or Hall Effect sensors, and then adjusting the voltage applied to the motor to maintain the desired speed.

In the BLDC motor, the back EMF (electromotive force) generated by the motor's rotor is proportional to the motor's speed. Therefore, by measuring the back EMF using a sensor, the speed control algorithm can determine the motor's speed and make adjustments to maintain a constant speed.

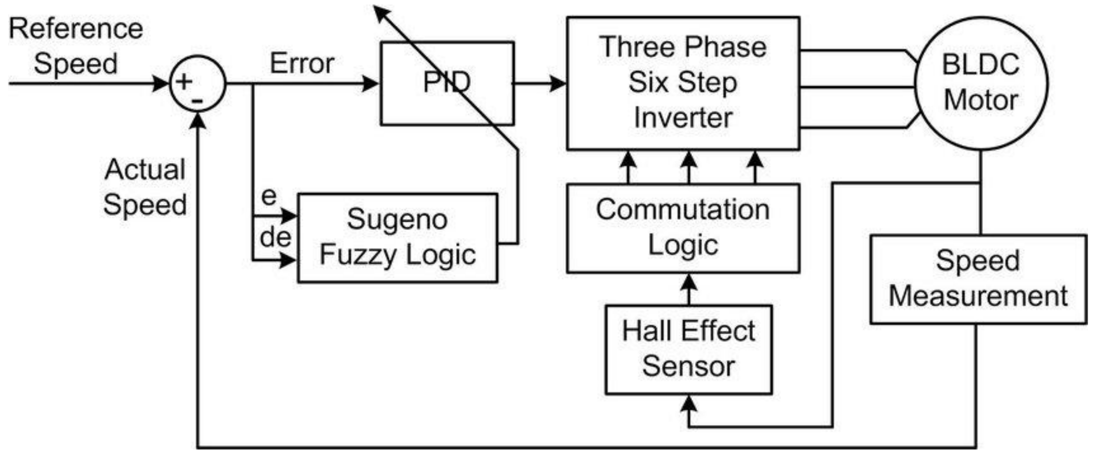

Figure 2. 3. Block Diagram of BLDC Motor Speed Control

The speed control algorithm in the BLDC motor typically involves using a proportional-integral (PI) controller to adjust the voltage applied to the motor based on the difference between the measured speed and the desired speed. The PI controller calculates an error signal based on the difference between the measured and desired speeds and uses this error signal to adjust the voltage applied to the motor.

The speed control algorithm can be further optimized by incorporating sensorless control techniques. Sensorless control algorithms use back EMF measurements to determine the motor's position and speed without the need for additional sensors. This technique reduces the cost and complexity of the motor control system and improves its reliability.

Another approach to speed control in BLDC motors is the use of field-oriented control (FOC). FOC is a control technique that decouples the motor's torque and flux, allowing for independent control of both parameters. FOC involves transforming the three-phase current into two orthogonal components: torque and flux. The torque component controls the motor's speed, while the flux component controls the motor's torque output. FOC provides high accuracy and efficiency in controlling the motor's speed and torque, making it an ideal choice for high-performance applications such as electric vehicles and industrial machinery.

Speed control is a critical component of the BLDC motor control system, and several control algorithms can be used to achieve optimal motor performance under different load conditions. The speed control algorithm typically involves using a PI controller to adjust the voltage applied to the motor based on the difference between the measured and desired speeds. Sensorless control and field-oriented control techniques can also be used to optimize the speed control process and improve the motor's performance.

2. 1. 3. Current Control

In the BLDC motor, the current flowing through the motor's stator coils determines the torque generated by the motor. Therefore, by regulating the current, the current control algorithm can adjust the motor's torque output and maintain optimal motor performance.

The current control process involves adjusting the phase current to maintain a constant torque output from the motor. The current control algorithm works by adjusting the PWM (pulse width modulation) signal applied to the motor to maintain a constant phase current. The phase current is measured using a current sensor, and the current control algorithm adjusts the PWM signal to maintain a constant current.

Current control is another essential component of the BLDC motor control system, as it regulates the current flowing through the motor's stator coils to ensure optimal motor performance and efficiency. The current control algorithm works by measuring the current flowing through the motor's stator using feedback from sensors such as shunt resistors or current sensors and adjusting the voltage applied to the motor to maintain the desired current level.

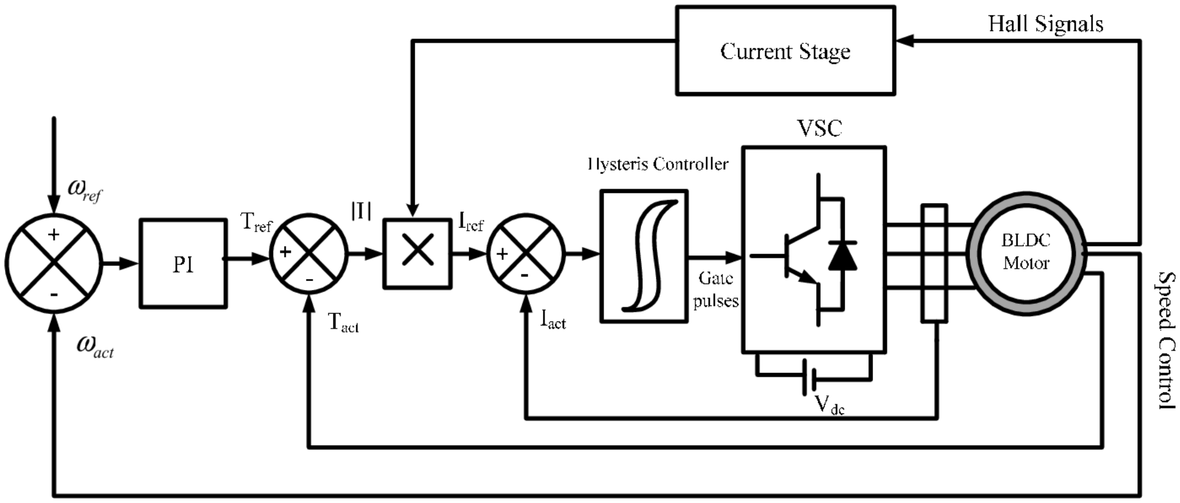

Figure 2. 4. Block Diagram of BLDC Motor Current Control

The current control algorithm in the BLDC motor typically involves using a proportional-integral (PI) controller to adjust the voltage applied to the motor based on the difference between the measured current and the desired current. The PI controller calculates an error signal based on the difference between the measured and desired currents and uses this error signal to adjust the voltage applied to the motor.

The current control algorithm can be further optimized by incorporating advanced control techniques such as space vector modulation (SVM). SVM is a control technique that uses a combination of pulse width modulation (PWM) and vector control to regulate the current flowing through the motor's stator coils. SVM can improve the motor's efficiency and reduce its noise and vibration levels.

Another approach to current control in BLDC motors is the use of direct torque control (DTC). DTC is a control technique that uses a lookup table to directly control the motor's torque and flux. DTC provides high accuracy and response speed, making it an ideal choice for high-performance applications such as electric vehicles and industrial machinery.

Current control is a critical component of the BLDC motor control system, and several control algorithms can be used to achieve optimal motor performance under different load conditions.

The current control algorithm typically involves using a PI controller to adjust the voltage applied to the motor based on the difference between the measured and desired currents. Advanced control techniques such as SVM and DTC can also be used to optimize the current control process and improve the motor's performance.

2. 1. 4. Third Harmonic Injection

Third harmonic injection is a technique used in the control of brushless DC motors (BLDC) to improve its performance. In this technique, a third harmonic signal is injected into the motor winding currents, which leads to the generation of a rotating magnetic field. This rotating magnetic field creates additional torque and helps the motor to achieve a higher speed than it would without the technique.

In our project, we have implemented third harmonic injection as a means of improving the motor's performance. We have used a software-based approach to implement this technique, which involves generating a third harmonic signal and adding it to the PWM signals that drive the motor. The added third harmonic signal leads to the generation of the rotating magnetic field, which improves the motor's speed and torque.

With a pure phase-neutral sinusoidal drive, the maximum phase-to-phase voltage is only roughly $0.86V_{bus}$. This can be improved by 'injecting' the sine wave with the third harmonic.

2. 1. 5. Clark Transformation (Alpha-Beta)

The Clark transformation (also called the αβ transformation, and occasionally called the Concordia transformation) is the projection of three separate sinusoidal phase values onto a stationary 2D axis. Clark transformation is a mathematical tool used to transform three-phase variables in a stationary reference frame into two-phase variables in a rotating reference frame. In our project, we have used the Clark transformation technique to control the brushless DC (BLDC) motor. The unsimplified Clark transformation equation is shown below.

The BLDC motor requires a set of three-phase currents to be controlled, which can be difficult to manage using traditional control techniques. By using the Clark transformation technique, we can transform the three-phase currents into two-phase currents that can be more easily controlled. The two-phase currents are then fed to the motor through PWM signals to drive its operation. The Clark transformation involves the use of a set of equations that transform the three-phase currents into two-phase currents. These equations take into account the phase angle of the currents and the orientation of the reference frame. The transformed currents are then used to calculate the motor's speed and position, which are used to adjust the PWM signals that drive the motor.

The direct component represents the amplitude of the magnetic field that is aligned with the rotor magnetic field, while the quadrature component represents the amplitude of the magnetic field that is perpendicular to the rotor magnetic field. These two components are used to generate the PWM signals that drive the motor.

$$I_{\alpha\beta\gamma} = TI_{abc} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

I_a = Current in motor winding A

I_b = Current in motor winding B

I_c = Current in motor winding C

$I_{\alpha\beta\gamma}$ = Clark transformed currents

When using a star-connected BLDC motor, I_c is 0,

$$I_{\alpha\beta\gamma} = TI_{abc} = \begin{bmatrix} 1 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} \end{bmatrix}\begin{bmatrix} I_a \\ I_b \end{bmatrix}$$

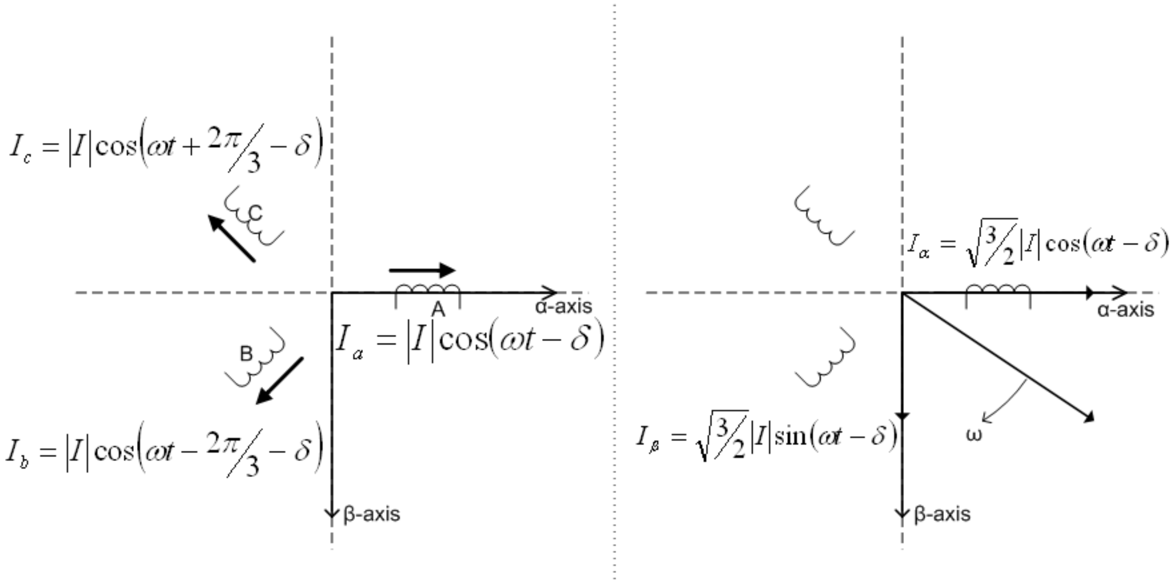

Figure 2. 5. Geometric Interpretation of the Clark (Alpha-Beta) Transformation

In our project, we have implemented the Clark transformation technique using a microcontroller and software-based approach. The technique has been shown to improve the motor's performance and efficiency, as well as reduce the risk of stalling. The results of our simulations and experimental tests have shown that the Clark transformation technique is an effective means of controlling the BLDC motor.

2. 1. 6. Park Transformation (dq)

Park transformation is a mathematical technique used to simplify the control of three-phase AC machines, such as the BLDC motor used in this project. In the Park transformation, the three-phase quantities (a, b, and c) are transformed into a two-phase rotating reference frame (d and q) that rotates with the rotor magnetic field.

The Park transformation is achieved by using the Clark transformation, which converts the three-phase quantities into two orthogonal components, one of which is in-phase with the original signal, and the other is 120 degrees out of phase. These two components are then transformed into the rotating reference frame using the rotor angle, which is obtained from the rotor position sensor.

$$I_{dqo} = TI_{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

I_{dqo} = Park Transformed currents

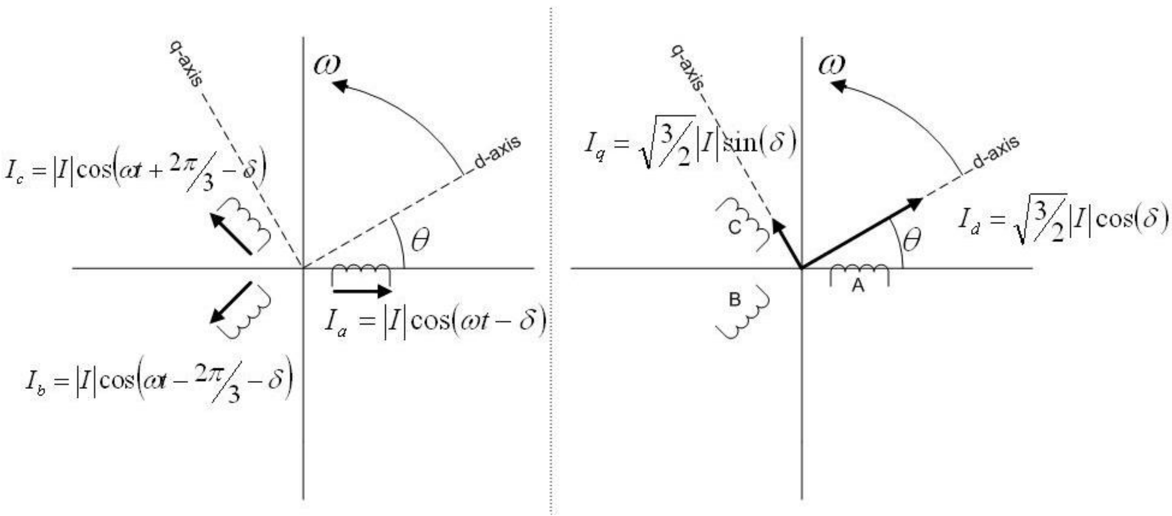

Figure 2. 6. Geometric Interpretation of the Park (dq) Transformation

Park transformation is a projection of three separate sinusoidal phase values onto a rotating 2D axis. The rotating axis (d, q) of the Park transformation rotates at the same speed as the rotor. When the projection occurs, the currents I_d and I_q remain constant (when the motor is at steady-state). It just so happens that I_d controls the magnetizing flux, while I_q controls the torque, and since both parameters are separate, we can control each individually.

In this project, the Park transformation is used to simplify the control of the BLDC motor by enabling the control of the motor in a two-phase rotating reference frame. This simplifies the control of the motor and allows for more efficient use of the available power.

The Park transformation is implemented using mathematical equations and algorithms in the microcontroller, which calculates the transformation in real-time based on the rotor position sensor feedback. The transformed values are then used by the motor controller to control the motor speed and torque.

2. 1. 7. Field-Oriented Control

Field Oriented control (FOC) is a method used to control the speed and torque of AC motors, including BLDC motors. In this project, FOC is used to control the BLDC motor. It involves transforming the three-phase AC signal into two orthogonal components: the direct current (DC) and quadrature current (QC) components. The DC component controls the motor's torque, while the QC component controls the motor's speed.

FOC involves using a controller to adjust the phase and amplitude of the DC and QC components to achieve the desired speed and torque. The controller uses feedback from sensors, such as encoders or Hall Effect sensors, to determine the motor's actual speed and position and adjust the control signals accordingly.

It is standard practice to set I_q to some value depending on the torque/speed required, while keeping I_d zero. However, there is a technique called flux weakening, and this is done by making I_d negative. It will allow the motor to spin faster than its rated speed, in a zone called ‘constant power’.

$$r = \tan(\theta)$$

where,

r = ratio ($I_d = rI_q$)
θ = drive angle

FOC typically requires three PID loops, one medium-speed loop for controlling the velocity and two high-speed loops for controlling I_d and I_q. There are two methods to measure the phase currents. The first involves just one current sense resistor on the DC return path from the motor, while the second requires three current-sense resistors, one on each leg of the three-phase bridge controlling the motor. The dynamic equations for FOC linking voltages, currents and torques are:

$$v_q = r_s I_q + L_q \frac{di_q}{dt} - w_e L_d I_d + w_e \lambda_f$$

$$v_d = r_s I_d + L_d \frac{di_d}{dt} - w_e L_q I_q$$

$$T_m = \frac{3}{2}\frac{P}{2}\left[\lambda_f I_q + \left(L_d - L_q\right) I_d I_q\right]$$

$$T_m = \frac{3}{2}\frac{P}{2}\lambda_f I_q = K_T I_q$$

FOC provides more precise control of the motor's speed and torque compared to other methods, such as trapezoidal control. It is widely used in industrial and automotive applications for its high performance and efficiency.

2. 2. HARDWARE COMPONENT SOURCING

The next step is the selection of hardware components for the control system. The hardware components include the microcontroller, ESC, sensors, and power supply. The selection of components will be based on factors such as cost, availability, and performance. Low-cost and easily available components will be preferred to make the control system accessible and cost-effective.

2. 2. 1. Electronic Speed Controller (ESC)

The ESC is a device that controls the power input to the BLDC motor by adjusting the duty cycle of the input voltage. It typically consists of power MOSFETs, control circuitry, and a microcontroller. The ESC receives input signals from the CCPM controller, which it uses to generate the appropriate control signals for the power MOSFETs. The ESC is typically connected between the power supply and the motor, and it works by modulating the power supplied to the motor to control its speed and direction of rotation.

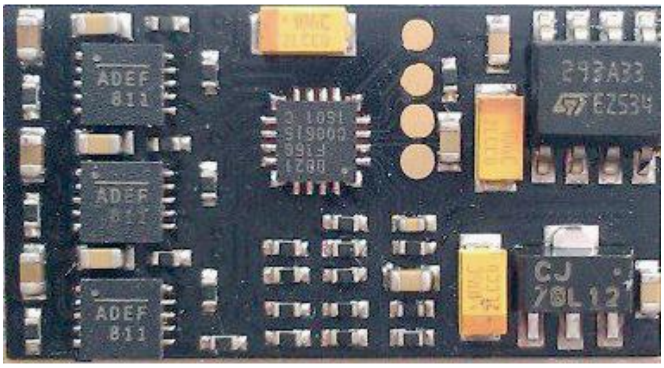

Figure 2. 7. Electronic Speed Control (ESC)

The ESC receives input signals from a controller such as a CCPM (Cyclic/Collective Pitch Mixing) controller, which sends a signal to the ESC to indicate the desired speed and direction of rotation of the motor. The ESC then adjusts the voltage and current supplied to the motor to achieve the desired speed and direction.

One of the key features of an ESC is its ability to modulate the power supplied to the motor using a technique called pulse width modulation (PWM). This involves rapidly turning the power on and off at a high frequency, and adjusting the duration of each pulse to control the average power supplied to the motor. By varying the duration of the pulses, the ESC can control the speed of the motor.

The ESC also typically includes a battery elimination circuit (BEC) that provides a regulated 5V output for powering other components in the system such as the CCPM controller. The BEC helps simplify the wiring and power management of the system.

In terms of specifications, ESCs are rated based on their maximum current and voltage ratings. The current rating indicates the maximum amount of current that the ESC can supply to the motor, while the voltage rating indicates the maximum voltage that the ESC can handle. It is important to select an ESC with appropriate ratings to ensure safe and reliable operation of the system.

In this case, the 30A ESC you are using is rated to handle a maximum current of 30A and a voltage range of 7-14V. Proper calibration and configuration of the ESC is important to ensure optimal performance and prevent damage to the motor or other components in the system. Proper integration and selection of the ESC can help ensure safe and efficient operation of the system.

- Current Rating: 30A
- Voltage Rating: 7-14V
- BEC (Battery Elimination Circuit) Type: Linear BEC
- BEC Output: 5V/2A

The ESC works by taking input signals from the CCPM (Cyclic/Collective Pitch Mixing) controller and modulating the power to the motor to control its speed and direction. The ESC also includes a BEC to provide a regulated 5V output for powering other components in the system such as the CCPM controller.

It is important to properly calibrate and configure the ESC before use to ensure optimal performance and prevent any damage to the motor or other components in the system. Proper integration of the ESC with the CCPM controller and power supply can help ensure the safe and reliable operation of the BLDC motor control system.

Alternative – REES52 30A ESC

To control the BLDC motor, we decided to use the REES52 30A electronic speed controller (ESC) instead of the ESC and CCPM controller. The REES52 30A ESC is a brushless DC motor controller that is commonly used in RC (radio control) models. The ESC is a closed-loop controller that senses the rotor position of the motor using the back-EMF (electromotive force) voltage and adjusts the phase commutation of the motor accordingly. The REES52 30A ESC has a built-in BEC (battery eliminator circuit) that provides a constant 5V power supply to the microcontroller and other peripheral devices.

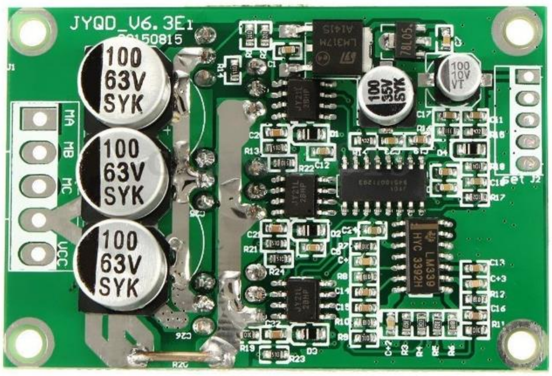

Figure 2. 8. REES52 JYQD V6.3E1

The REES52 30A ESC has three motor wires (red, black, and yellow) and four signal wires (red, black, white, and blue). The motor wires are connected to the three-phase terminals of the BLDC motor, and the signal wires are connected to the microcontroller's PWM (pulse width modulation) pins. The PWM signal is used to vary the duty cycle of the signal, which in turn adjusts the motor speed. The REES52 30A ESC also has a set of programming pins that can be used to configure the ESC's settings such as the timing, throttle range, and braking. These settings can be programmed using an external programming card or through the microcontroller's software.

To use the REES52 30A ESC in this project, we first had to calibrate the ESC by following the manufacturer's instructions. We connected the ESC to the power supply and then connected the throttle signal wire to a servo tester. We then followed the steps outlined in the manual to calibrate the ESC's throttle range and timing. Once the ESC was calibrated, we connected it to the microcontroller's PWM pins and wrote a simple software program to vary the motor speed using PWM signals.

We tested the REES52 30A ESC by running the BLDC motor at different speeds and observing the motor's response. We also tested the braking function by abruptly stopping the motor and observing its deceleration. We found that the REES52 30A ESC provided smooth and precise motor control, and the built-in BEC ensured a stable power supply to the microcontroller and other peripheral devices. REES52 30A ESC is a reliable and cost-effective solution for controlling BLDC motors in projects such as electric vehicles. Its compact size, built-in BEC, and easy-to-use programming interface make it an ideal choice for hobbyists and DIY enthusiasts. By using the REES52 30A ESC in project, we were able to simplify the hardware design and achieve accurate and stable motor control.

2. 2. 2. CCPM Consistency Master Controller

The CCPM controller (Cyclic/Collective Pitch Mixing controller) is a device that generates the input signals for the ESC. It receives input signals from the motor's sensing devices and user input (such as joystick inputs), and generates the appropriate control signals for the ESC. The CCPM controller typically includes a microcontroller, power regulation circuitry, and user interface components.

CCPM, or Cyclic/Collective Pitch Mixing, is a control system used in radio-controlled devices. It is designed to allow precise control over the pitch of the rotor blades, which in turn controls the lift and direction. CCPM can also be used to control the speed and direction of a brushless DC (BLDC) motor.

Figure 2. 9. CCPM Control System

In a CCPM system, three servos are used to control the pitch of the rotor blades. The servos are connected to a control board that is programmed to translate the input signals from the remote control into the appropriate servo movements. In the context of BLDC motor control, CCPM can be used to control the speed and direction of the motor. The CCPM controller receives input signals from the user or other external sensors, and uses these signals to adjust the speed and direction of the motor. By adjusting the pulse width modulation (PWM) signals sent to the ESC, the CCPM controller can control the speed of the motor.

One of the key advantages of CCPM is its ability to provide precise and responsive control over the motor. By using three servos to control the motor, the CCPM system can make small adjustments to the speed and direction of the motor in real-time, allowing for smooth and accurate control. Additionally, CCPM can be used to control multiple motors simultaneously, allowing for more complex and advanced control systems.

The CCPM controller is being used to control the speed and direction of the BLDC motor in conjunction with the ESC. The CCPM controller sends input signals to the ESC, which adjusts the voltage and current supplied to the motor to achieve the desired speed and direction. By integrating the CCPM controller with the ESC and other components in the system, you can achieve precise and reliable control over the motor.

Overall, CCPM is a powerful control system that can be used to control the speed and direction of a brushless DC motor with high precision and responsiveness. By properly integrating and configuring the CCPM controller with the ESC and other components in the system, you can achieve safe and efficient operation of the BLDC motor control system.

2. 2. 3. Power Supply

A suitable power supply is required to provide the required voltage and current to the ESC and the BLDC motor. The power supply should be capable of providing a stable voltage and current with low noise to ensure the smooth operation of the motor.

The power supply is a critical component in any electronic system, and in this case, it is responsible for providing the necessary voltage and current to drive the BLDC motor. The power supply used in this system is a regulated power supply, which means that it is designed to provide a consistent and stable output voltage, regardless of changes in input voltage or load.

A regulated power supply typically consists of two main components: a transformer and a voltage regulator. The transformer is responsible for stepping down the incoming AC voltage to a lower AC voltage, which is then rectified to produce a DC voltage. The voltage regulator then adjusts the DC voltage to the desired level, providing a consistent output voltage to the system.

In this system, the regulated power supply is used to provide the necessary voltage and current to drive the ESC, which in turn controls the speed and direction of the BLDC motor. The power supply must be able to provide enough current to meet the demands of the motor, while also maintaining a stable and consistent voltage output.

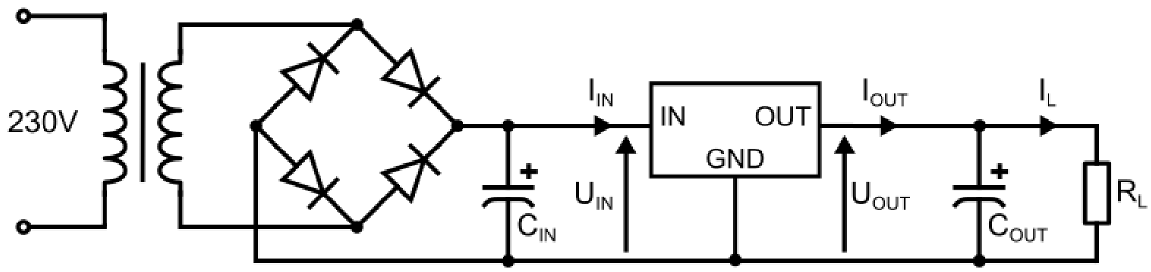

Figure 2. 10. Regulated Power Supply

It's important to select a power supply that is appropriate for this system's needs. This means considering the voltage and current requirements of the motor, as well as any other components in the system that require power. Additionally, it's important to ensure that the power supply can operate safely and reliably in the intended environment.

The regulated power supply used in this BLDC motor control system is responsible for providing a stable and consistent output voltage to drive the ESC and motor. By selecting an appropriate power supply and ensuring proper operation and safety measures, you can ensure reliable and efficient operation of the BLDC motor control system.

2. 2. 4. BLDC Motor

A brushless DC motor is required for the system. The motor should be selected based on its electrical specifications (such as voltage, current, and power rating), physical dimensions, and torque characteristics. BLDC stands for Brushless DC motor, which is a type of motor that uses electronic commutation instead of brushes to control the motor's rotation. Unlike brushed DC motors, which use brushes to make physical contact with the commutator, BLDC motors use a series of electromagnets to rotate the motor shaft.

The BLDC motor used in this system is the A2212/13T 1400kv model. The model number refers to the size and specifications of the motor, with the "A" indicating the size and the "2212" indicating the stator diameter and length. The "13T" refers to the number of turns in each of the three motor windings, and the "1400kv" refers to the motor's speed constant, which is measured in RPM per volt.

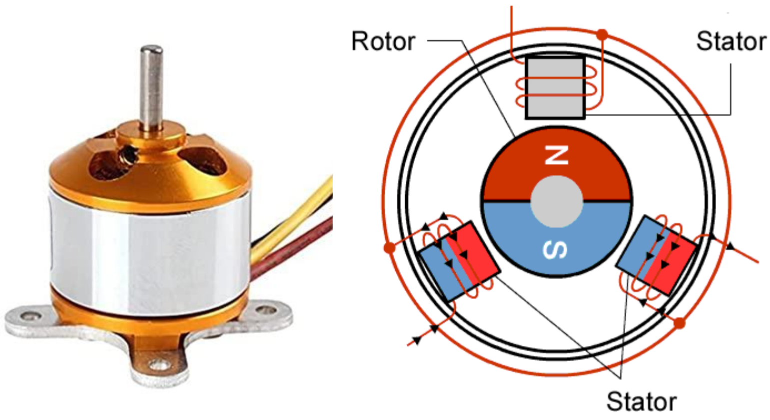

Figure 2. 11. BLDC Motor

The BLDC motor consists of a rotor and a stator. The stator is the stationary part of the motor, consisting of a series of electromagnets arranged around the motor's circumference. The rotor is the rotating part of the motor, consisting of a series of permanent magnets that are magnetized in a specific pattern.

In operation, the BLDC motor is controlled by a series of electronic pulses that are sent to the motor's windings. These pulses are timed to activate each winding at the correct time, causing the motor to rotate.

KV (RPM/V)	**Propeller**	**Load Current (A)**	**Pull (g)**	**Power (W)**	**Efficiency (g/W)**
930	1060	9.8	660	109	6.1
1000	1047	15.6	885	173	5.1
1400	9050	19.0	910	210	4.3
1800	8060	20.8	805	231	3.5
2200	6030	21.5	732	239	3.1
2450	6x3	25.2	815	280	2.9

Table 2. 3. Motor Performance Data

Electrical Characteristics	**Configuration**
Kv	1000 RPM/V
Max Efficiency	80%
Max Efficiency Current	4 - 10A (>75%)
No Load Current	0.5A @10V
Resistance	0.090 ohms

Mechanical Characteristics	**Configuration**
Weight	52.7 g / 1.86 oz.
Shaft Diameter	3.2 mm
Size	28 mm dia. x 28 mm bell length
Poles	14
Model Weight	300 - 800g

Table 2. 4. Electrical & Mechanical Characteristics of A2212/13T BLDC Motor

The speed and direction of the motor are controlled by varying the frequency and timing of these pulses. BLDC motors are also capable of higher speeds and more precise control, making them ideal for applications such as robotics and electric vehicles. The A2212/13T 1400kv BLDC motor used in this control system is a popular and reliable choice for various applications.

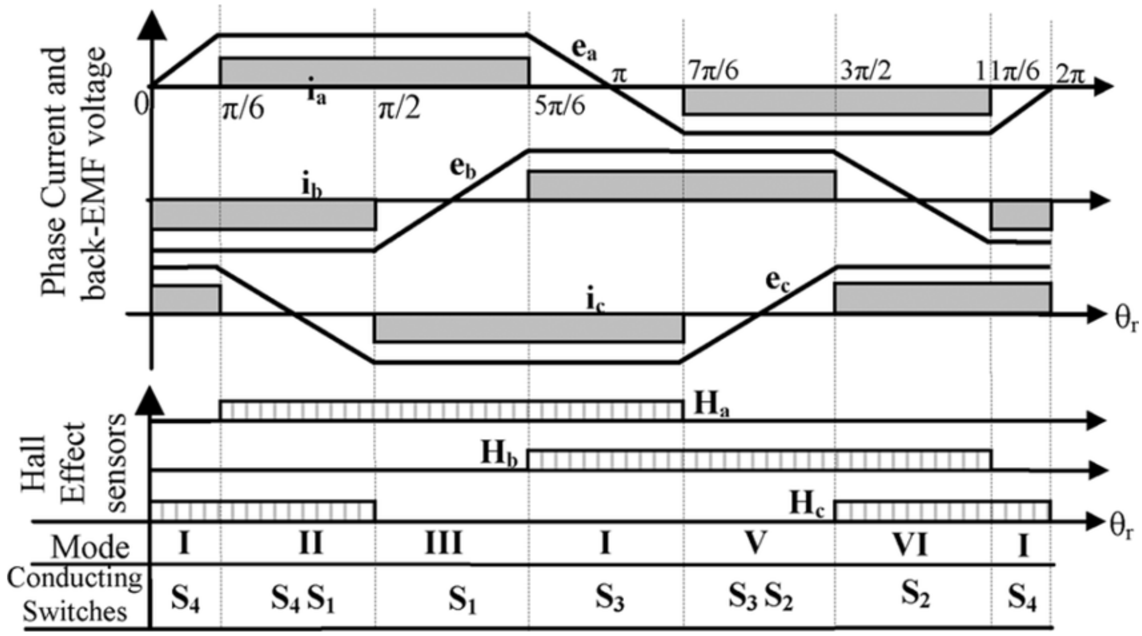

Figure 2. 12. Signalling Waveform Models

By understanding the principles of operation and selecting an appropriate motor for this system's needs, you can achieve efficient and reliable control of this BLDC motor. Based on these specifications, a regulated power supply of 7-14V can be used to power the motor. A 30A electronic speed controller (ESC) is recommended for controlling the motor's speed and power output.

2. 2. 5. Wiring and Connectors

Wiring and connectors are required to connect the ESC, CCPM controller, power supply, and motor. The wiring should be of appropriate size and material to handle the current and voltage levels involved. The connectors should be reliable and secure to ensure proper connection and operation of the system.

The motor has three wires, typically colored red, blue, and yellow that correspond to the three windings. These wires are connected to the three outputs on the ESC (Electronic Speed Controller), which is responsible for providing power and control signals to the motor. The ESC typically has a set of three motor outputs that are labelled A, B, and C, and the wires from the motor are connected to these outputs in a specific order. The correct order is determined by the motor's rotation direction and can be found in the motor's datasheet.

The regulated power supply is typically connected to the ESC's battery input terminals, which are labelled positive and negative. The power supply must be capable of providing enough voltage and current to meet the requirements of the motor and ESC. It is important to ensure that the voltage rating of the power supply matches the voltage rating of the motor and ESC, and that the current rating is sufficient to handle the maximum current draw of the motor.

The CCPM controller, which is responsible for translating the user's input commands into control signals for the ESC. The CCPM controller typically has three input channels, which are connected to the receiver controller. These channels are typically labelled Aileron, Elevator, and Throttle, and are used to control the roll, pitch, and speed of the motor, respectively. The CCPM controller also has three output channels, which are connected to the ESC's control inputs. These channels are typically labelled A, B, and C, and are used to send the control signals to the motor.

- **Motor and ESC Connections -** The motor was connected to the ESC using three wires, and the ESC was connected to the power supply.
- **CCPM Controller Connections -** The CCPM controller was connected to the ESC using servo connectors. The CCPM controller was then calibrated to ensure that it was functioning correctly.

When selecting hardware components for a BLDC motor control system using an ESC and a CCPM controller, it is important to consider factors such as cost, performance, reliability, and ease of integration. The components should be carefully chosen to ensure they are compatible with the motor's electrical specifications and provide the necessary features and functionality to achieve the desired performance. Proper selection and integration of these hardware components are critical to ensuring the successful operation of the BLDC motor control system.

2. 3. CONTROL ALGORITHM DEVELOPMENT

The third step is the development of the control system. The control algorithm designed in the first step will be implemented using the selected microcontroller, and the control signals will be sent to the ESC to control the motor speed and torque. The sensors, such as encoders and Hall Effect sensors, will be used to provide feedback to the microcontroller, which will adjust the control signals accordingly. The power supply will be used to provide power to the motor and the control system.

The control system management in this project is a vital component that ensures the proper functioning and performance of the BLDC motor control system. It involves the implementation of various control algorithms and signal processing techniques to regulate the motor's speed and current and maintain the desired position and motion. The control system management can be divided into three main areas: commutation, speed control, and current control.

Commutation involves the precise timing of the voltage switching to ensure that the motor rotates in the desired direction. Speed control regulates the motor's speed based on the signals received from the CCPM controller, and current control regulates the current flowing through the motor's phases to prevent damage and ensure efficient operation.

The control system management for this project is crucial for the overall performance of the BLDC motor control system. It involves the use of various control algorithms and signal processing techniques to regulate the motor's speed, current, and position. The commutation algorithm is used to ensure that the motor rotates in the desired direction. It is achieved by accurately timing the voltage switching to the motor's phases.

The speed control algorithm is used to regulate the motor's speed based on the signals received from the CCPM controller. This algorithm works by adjusting the voltage supplied to the motor based on the desired speed. It ensures that the motor's speed remains constant under varying load conditions and external disturbances. The current control algorithm is used to regulate the current flowing through the motor's phases. This algorithm is important to prevent damage to the motor and ensure efficient operation. It works by monitoring the current flowing through the motor and adjusting the voltage supplied to the motor to keep the current within safe limits.

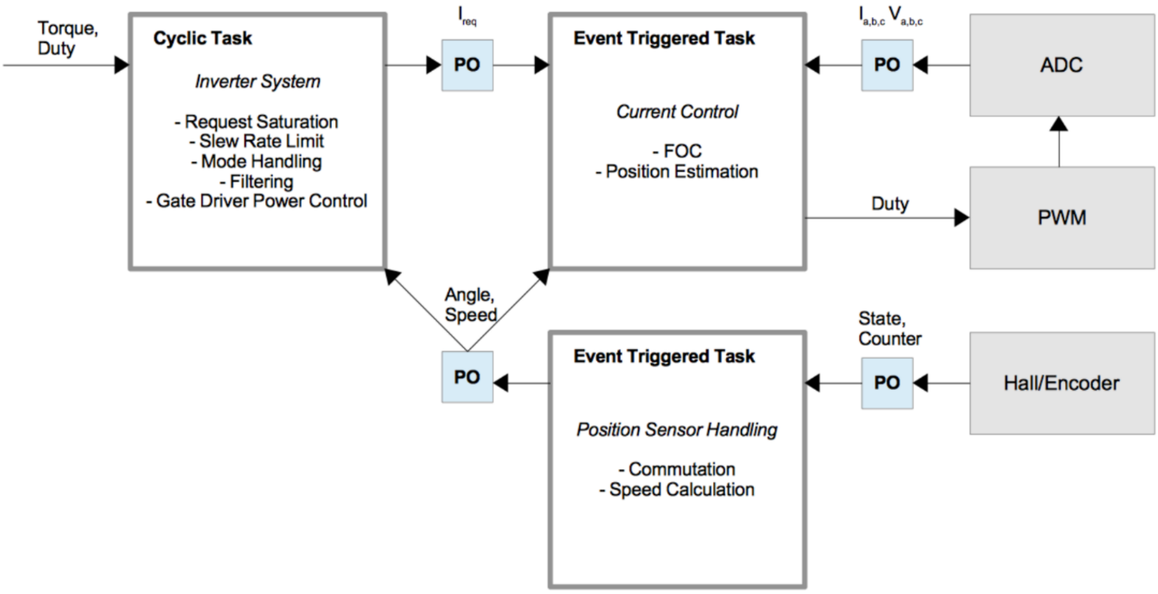

Figure 2. 13. Control System Algorithm

To implement these control algorithms, various signal processing techniques are used, including filtering, modulation, and feedback control.

These techniques help to remove unwanted noise from the signals and ensure that the control system responds quickly and accurately to changes in the motor's speed and position. Proper implementation of the commutation, speed control, and current control algorithms, along with the signal processing techniques, requires a thorough understanding of the motor's characteristics and the control system's limitations and requirements.

The implementation should be carefully designed and tested to ensure the safe and efficient operation of the motor and provide a smooth and accurate control system for the user. The implementation of robust control algorithms and signal processing techniques is necessary to accurately and reliably regulate the motor's speed, current, and position. It requires a thorough understanding of the motor's characteristics and the control system's limitations and requirements.

Control algorithm design is a crucial aspect of any control system design. It involves the development of a mathematical model that describes the behaviour of the system and the design of a controller that will regulate the system to achieve the desired performance. In this project, the control algorithm is designed for the BLDC motor control system using the IR2110 gate driver IC, which drives the power MOSFETs to regulate the motor speed.

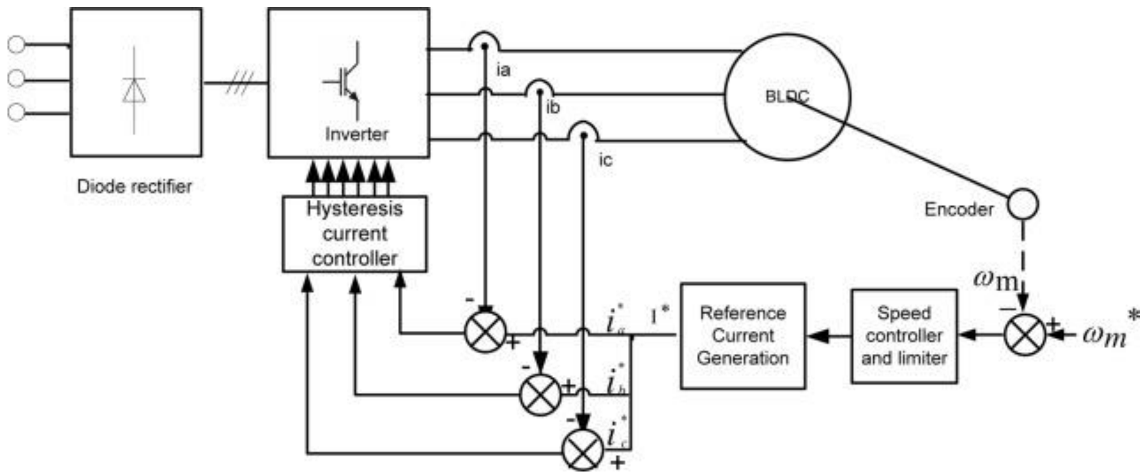

Figure 2. 14. Closed Loop Rapid Control

The control algorithm is based on a closed-loop control system, which continuously monitors the motor's speed and adjusts the power input to maintain a constant speed. The control algorithm consists of several components, including the feedback loop, the reference generator, and the controller.

The feedback loop is responsible for measuring the motor's speed and providing feedback to the controller. The controller compares the measured speed with the desired speed and generates a control signal to adjust the power input to the motor. The reference generator generates the desired speed profile based on the user's input.

The control algorithm is implemented in software on the microcontroller or hardware in the case of an ESC and CCPM controller. In this project, the control algorithm is implemented in hardware using the IR2110 gate driver IC and the power MOSFETs. The design of the control algorithm is critical to achieving the desired performance of the motor control system. A well-designed control algorithm can provide smooth operation, fast response, and robustness to disturbances. It is essential to carefully select the control parameters and tune the controller to achieve the desired performance.

Once the control system was developed and tested, it was integrated into the final product. The final product consisted of the BLDC motor, ESC, CCPM controller, and control system.

2. 4. PID CONTROLLER DESIGN

A PID controller is a feedback control system that uses a combination of proportional (P), integral (I), and derivative (D) terms to adjust the control variable and maintain the desired set-point. In the case of a BLDC motor control system, a PID controller can be used to regulate the motor speed or current.

The proportional term produces an output that is proportional to the error between the desired set-point and the actual motor speed or current. The integral term accumulates the error over time and produces an output that is proportional to the integral of the error. The derivative term produces an output that is proportional to the rate of change of the error.

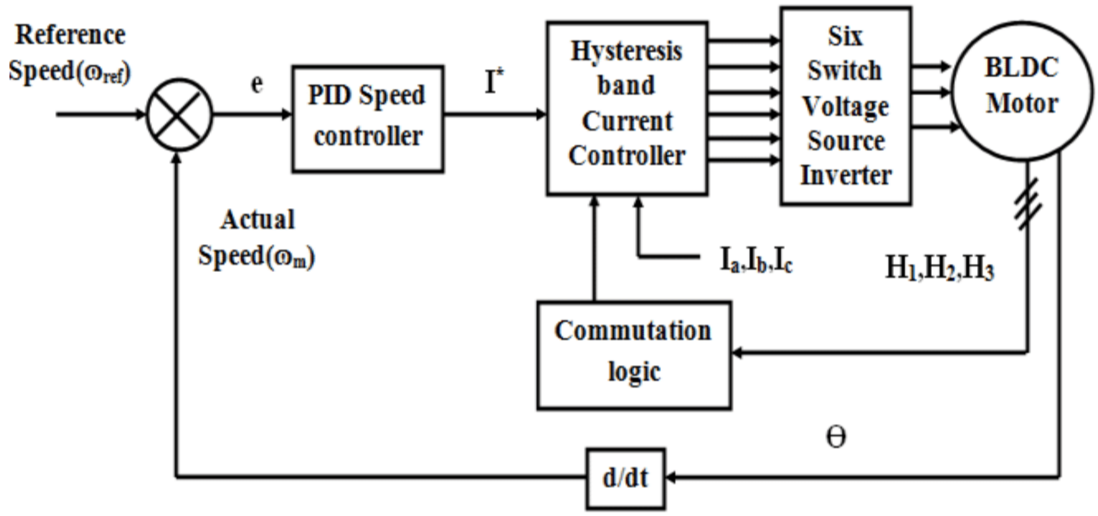

Figure 2. 15. PID Controller Design

The PID controller design involves tuning the controller gains (Kp, Ki, and Kd) to achieve the desired performance. The tuning process involves selecting appropriate values for these gains such that the controller responds quickly to changes in the set-point while maintaining stability and avoiding overshoot or oscillation.

There are various methods for tuning PID controllers, including the Ziegler-Nichols method, Cohen-Coon method, and trial-and-error method. In general, the tuning process involves iteratively adjusting the controller gains and observing the response of the system to step changes in the set-point or disturbances.

One important consideration in the design of a PID controller for a BLDC motor control system is the selection of the control variable. Depending on the specific application, the control variable may be the motor speed, motor current, or another relevant variable.

Additionally, the PID controller may need to be implemented using a microcontroller or other hardware platform, which requires consideration of the available computational resources and programming capabilities. PID controller is a commonly used control algorithm in BLDC motor control. It stands for Proportional-Integral-Derivative controller.

The PID controller continuously calculates an error signal, which is the difference between the desired speed and the actual speed of the motor. It then uses this error signal to adjust the input voltage to the motor in order to reduce the error and bring the motor to the desired speed.

The Proportional term in the PID controller output is proportional to the error signal. The Integral term is proportional to the integral of the error signal over time, and the Derivative term is proportional to the derivative of the error signal with respect to time. The proportional term is responsible for the quick response of the system to changes in the error signal, while the integral term helps to eliminate steady-state errors in the system. The derivative term helps to reduce overshoot and dampen the system response.

The tuning of the PID controller involves adjusting the proportional, integral, and derivative gains to achieve a stable and responsive system. This can be done manually by trial and error, or automatically using methods such as Ziegler-Nichols or Cohen-Coon methods.

The tuning process involves adjusting the gains until the system has the desired response, such as minimal overshoot, fast settling time, and minimal steady-state error. The effectiveness of the PID controller in controlling the BLDC motor depends on the accuracy of the motor model and the choice of tuning parameters.

Proper tuning can lead to stable and responsive motor control, while poor tuning can lead to instability, oscillations, and inefficient performance. Data collection is important in the tuning process as it allows for the analysis of the motor's response to changes in the input voltage and the PID controller gains.

This can be done by measuring the motor speed and current using sensors, or by using simulation software to simulate the motor behaviour. The collected data can then be used to adjust the PID controller gains for optimal performance.

2. 5. CONTROL LOOP TUNING

Control loop tuning is an important step in designing a control system that performs well. It involves adjusting the parameters of the control algorithm to achieve the desired response of the system.

There are several methods for control loop tuning, including manual tuning, Ziegler-Nichols method, and model-based tuning. Manual tuning involves adjusting the parameters of the controller until the desired response is achieved.

Ziegler-Nichols method is a popular method for tuning PID controllers, which involves finding the ultimate gain and ultimate period of the system and using them to calculate the controller parameters. Model-based tuning involves using mathematical models of the system to optimize the controller parameters.

In this project, manual tuning will be used to tune the PID controller. This involves adjusting the proportional, integral, and derivative gains until the system response meets the desired specifications. The tuning process will involve performing step tests and analyzing the response of the system to determine the appropriate gain values.

The tuning process involved selecting appropriate values for the proportional (Kp), integral (Ki), and derivative (Kd) gains of the controller. These values were adjusted based on the response of the system to the input signal.

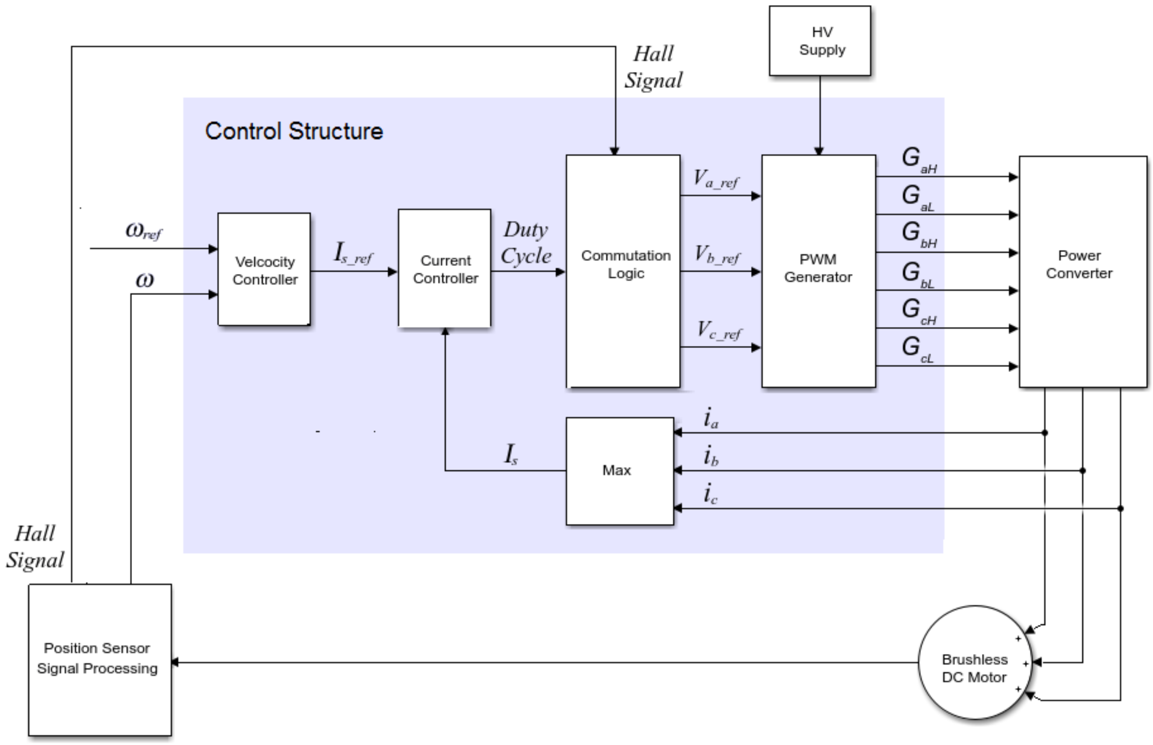

Figure 2. 16. Control Structure

To tune the controller, the system was subjected to a step input signal, and the response of the system was analyzed. The proportional gain was initially set to a small value, and then it was gradually increased until the system began to oscillate.

At this point, the gain was reduced to a value slightly below the oscillation point.

Next, the integral gain was increased until the steady-state error was reduced to zero. However, care was taken not to increase the integral gain too much, as this could lead to instability.

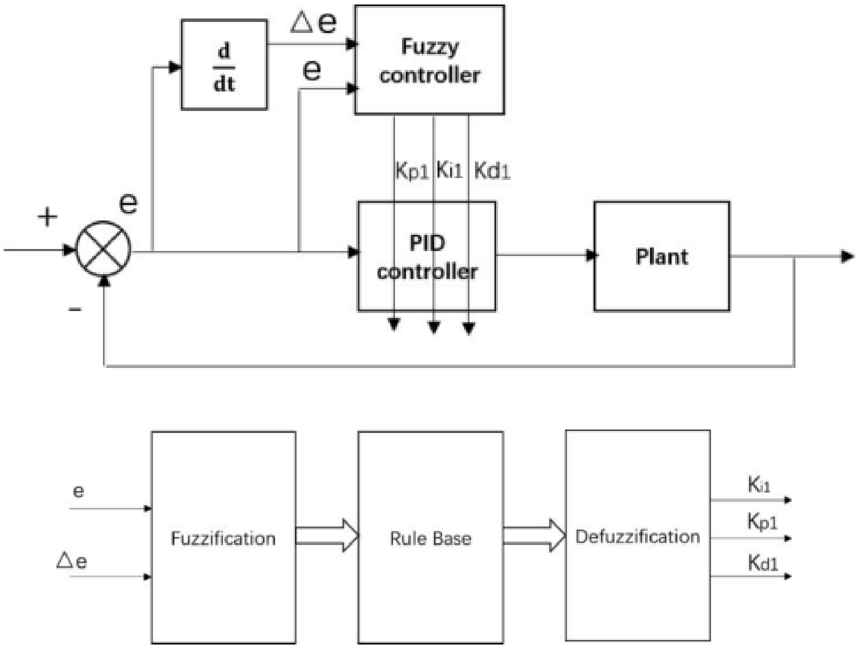

Figure 2. 17. Self-Tuning Fuzzy Model

Finally, the derivative gain was added to improve the controller's response to sudden changes in the input signal. The derivative gain was adjusted by observing the system's response to a sudden change in the input signal and making sure that the system did not oscillate.

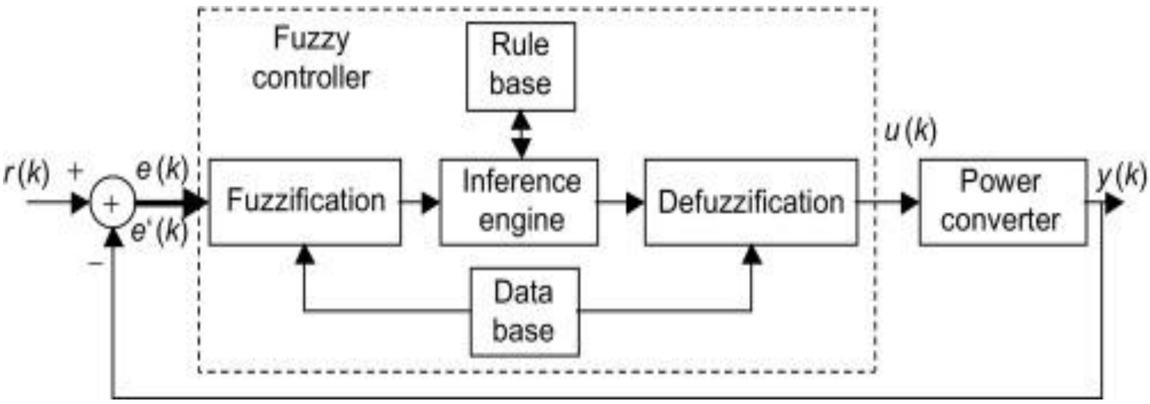

Figure 2. 18. Fuzzy Controller Structure

The tuning process was repeated several times until the desired response was achieved. During the tuning process, the performance of the system was evaluated using various metrics such as rise time, settling time, overshoot, and steady-state error.

2. 5. 1. Ziegler-Nichols Method

The Ziegler-Nichols method is a popular approach for tuning PID controllers. This method involves performing step tests on the system to determine its response characteristics, such as the time delay, rise time, and overshoot. From these parameters, the Ziegler-Nichols method provides a set of tuning coefficients that can be used to adjust the PID controller's proportional, integral, and derivative gains.

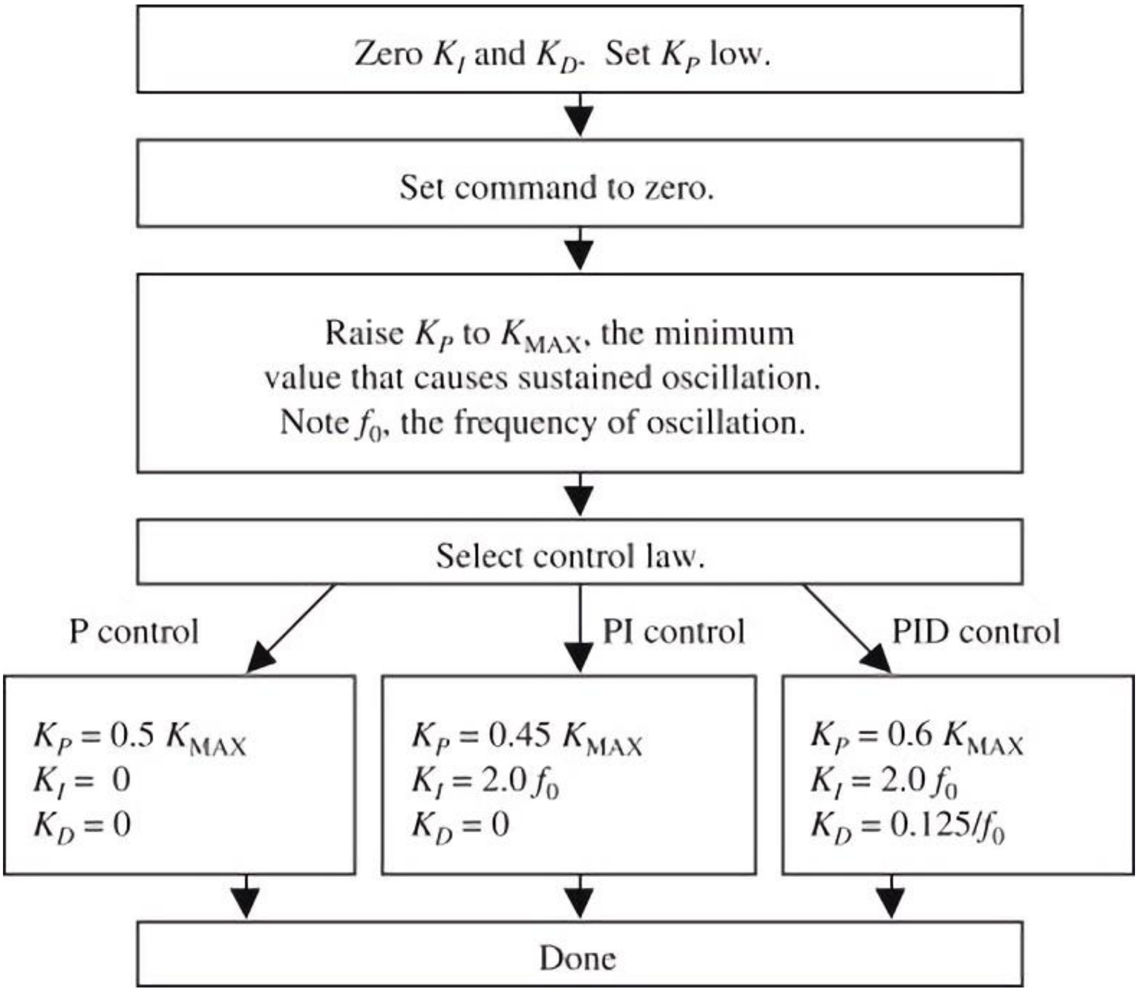

Figure 2. 19. Ziegler Nichols Tuning Algorithm

To implement the Ziegler-Nichols method for this project, we would first need to perform step tests on the BLDC motor and analyze its response characteristics. We can do this by commanding the motor to rotate at a certain speed and measuring its output using sensors or other means.

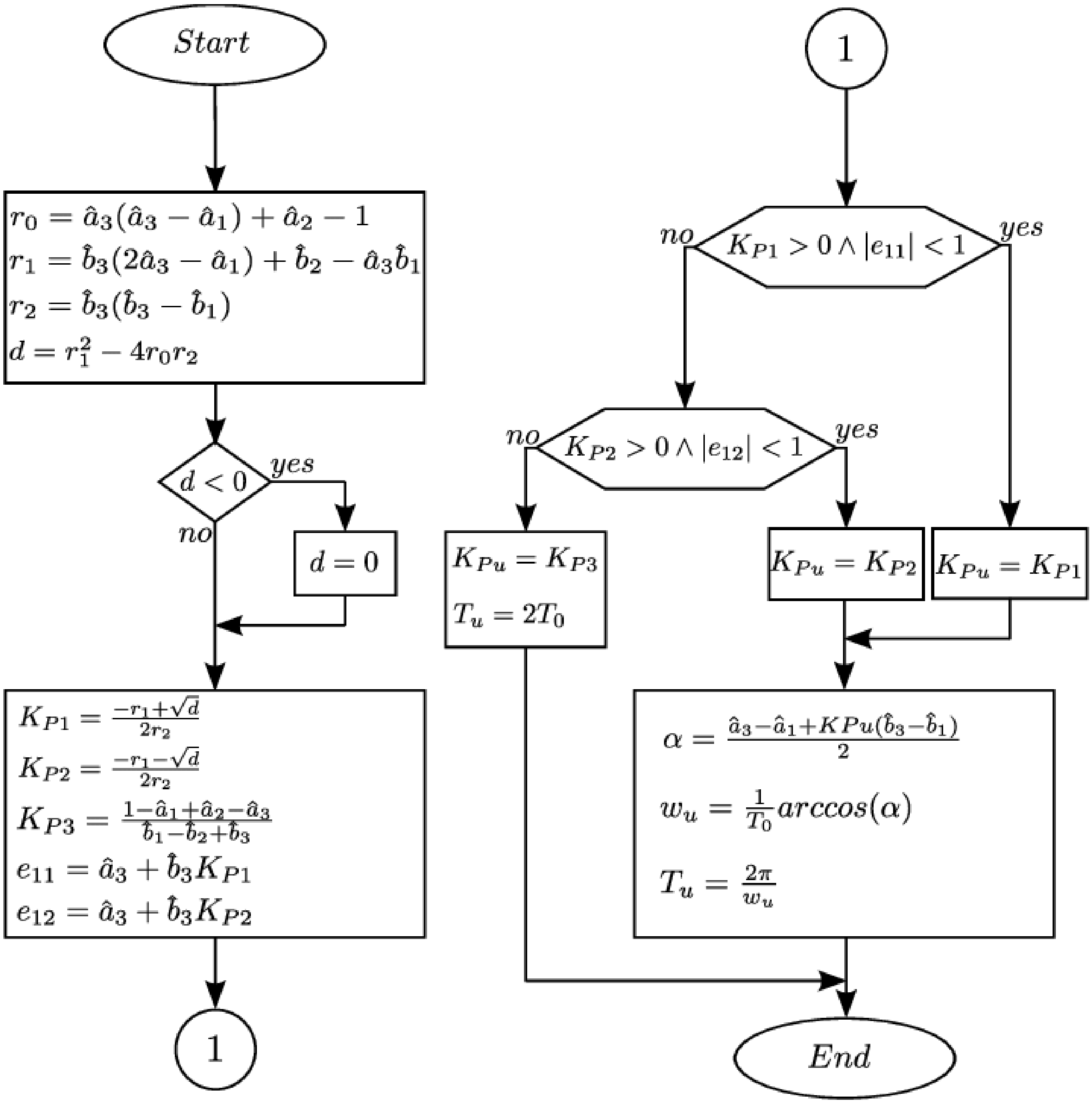

Figure 2. 20. Ziegler Nichols Tuning Flow

Once we have gathered the necessary data, we can use the Ziegler-Nichols method to compute the appropriate tuning coefficients for the PID controller.

The Ziegler-Nichols method provides three different sets of coefficients, each corresponding to different levels of controller performance: "aggressive", "moderate", and "conservative". We would need to select the appropriate set of coefficients based on the desired performance characteristics of the control system.

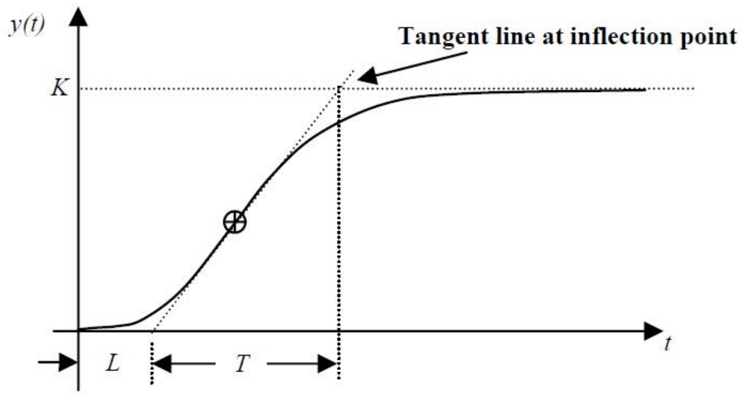

Figure 2. 21. Ziegler Nichols Tangent Waveform

After obtaining the tuning coefficients, we can implement them in the control algorithm and test the system to see if it is behaving as expected.

2. 5. 2. Cohen-Coon Method

The Cohen-Coon method is a popular method for tuning PID controllers. In this project, the Cohen-Coon method was used to tune the PID controller for the BLDC motor. The method involves performing step tests on the system and using the data to calculate the parameters for the PID controller. The steps involved in using the Cohen-Coon method are as follows:

- Perform a step test on the system by applying a step change in the input and measuring the response of the system.
- Determine the process gain (Kp) and time constant (Tp) of the system from the step response data.
- Use the following equations to calculate the PID parameters:
    - Kp = (1.35 / Kp) * (Tp / (Tm * (1 + (0.35 * Tp / Tm))))
    - Ti = 2.5 * Tp
    - Td = 0.37 * Tp

Where Kp is the proportional gain, Ti is the integral time, Td is the derivative time, Tp is the process time constant, and Tm is the time delay of the system.

- Implement the PID controller with the calculated parameters and test the system to ensure that it is performing as expected.

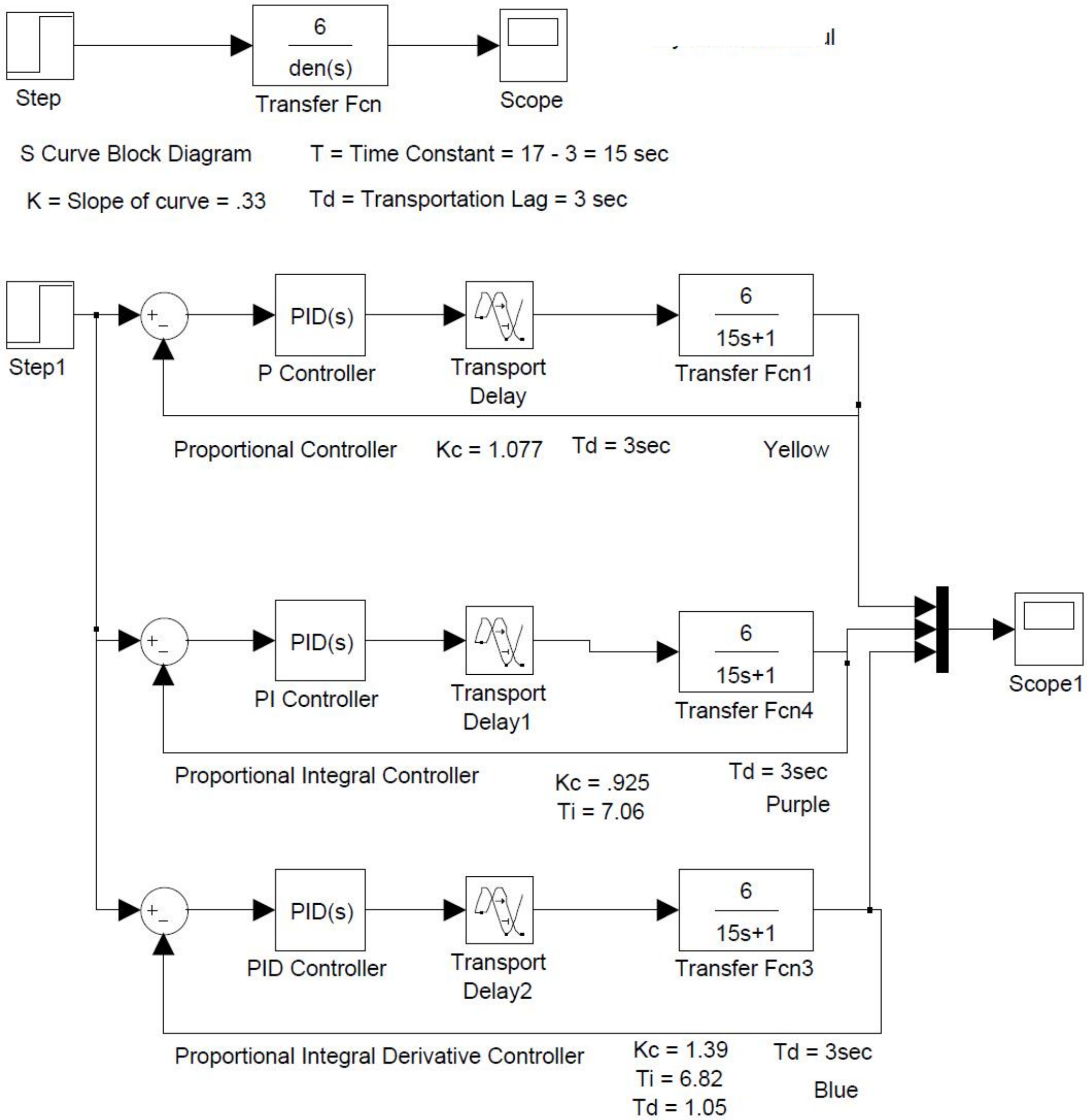

Figure 2. 22. Cohan-Coon Tuning Algorithm

The Cohen-Coon method is a simple and effective way to tune PID controllers, and it can be used for a wide range of systems. However, it should be noted that the method is an approximation and may not always provide the best tuning parameters for the system.

2. 5. 3. Trial-and-Error Method

The trial-and-error method, also known as manual tuning, is a common method used for PID controller tuning. In this method, the PID gains are adjusted manually until the desired control performance is achieved. To implement the trial-and-error method in this project, the following steps can be taken:

- Set the integral and derivative gains to zero, and the proportional gain to a small value.
- Test the system response to a step input and observe the overshoot and settling time.
- Increase the proportional gain until the system response becomes oscillatory.
- Adjust the derivative gain to reduce overshoot and settling time.
- Adjust the integral gain to eliminate steady-state error, if present.

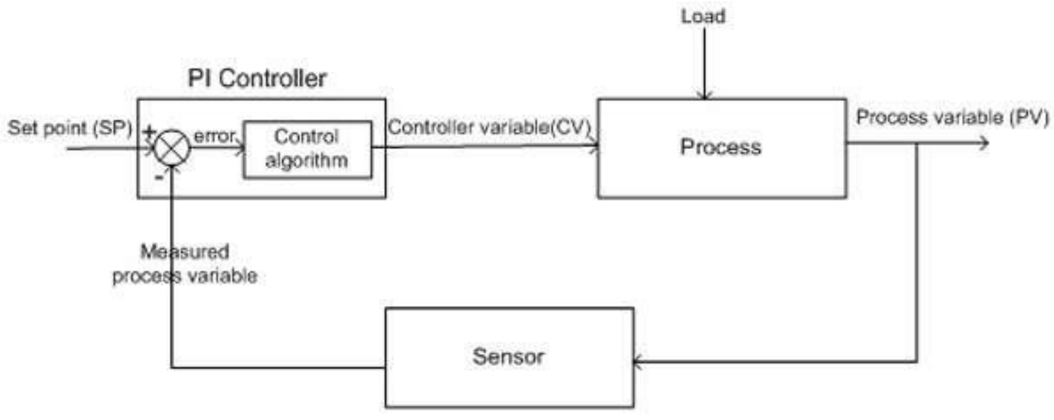

Figure 2. 23. Trail-&-Error Tuning Algorithm

The process is repeated until the desired control performance is achieved. It is important to note that the trial-and-error method can be time-consuming and may require several iterations before optimal gains are obtained. Additionally, it may not be suitable for systems with nonlinear dynamics or time-varying parameters.

2. 6. TESTING AND EVALUATION

The final step in the methodology is the testing and evaluation of the control system. The performance of the control system will be evaluated under different operating conditions, such as different loads and speeds. The system will be compared with existing control systems, such as the PID controller and CCPM controller, to evaluate its performance and efficiency. The results of the experiments will be analysed, and any limitations or areas for improvement will be identified.

Testing and evaluation of the BLDC motor control system is an important aspect of the project. It involves verifying the system's performance and ensuring that it meets the project's objectives. The testing and evaluation process can be broken down into several stages, each with its own set of objectives and procedures.

The first stage of testing involves verifying the wiring and connections between the components of the system. This includes checking the connections between the ESC, CCPM controller, and the motor, as well as the power supply connections. This stage is crucial to ensure that the system is correctly wired and that all components are receiving the proper voltage and signals.

The second stage involves testing the motor's commutation and ensuring that it rotates in the desired direction. This is done by providing the motor with different input signals and observing its response. The timing and sequence of the input signals are adjusted until the motor rotates smoothly in the desired direction.

The third stage involves testing the speed control algorithm and verifying that the motor's speed can be regulated accurately. This is done by providing the motor with different input signals and measuring its response. The accuracy and responsiveness of the speed control algorithm are evaluated and adjusted as necessary to achieve the desired performance.

The fourth stage involves testing the current control algorithm and ensuring that the current flowing through the motor's phases is within safe limits. This is done by providing the motor with different input signals and measuring the current flowing through its phases. The current control algorithm is evaluated and adjusted as necessary to ensure safe and efficient operation of the motor.

The final stage involves evaluating the overall performance of the system and verifying that it meets the project's objectives. This includes evaluating the system's responsiveness, accuracy, and efficiency under different load conditions and external disturbances. The system's performance is compared to the project's objectives, and adjustments are made as necessary to ensure that the objectives are met.

The testing and evaluation process is iterative, and adjustments may need to be made to the control system's algorithms and parameters as the testing progresses. The results of the testing and evaluation process are documented and presented in the project report, along with recommendations for further improvements to the system.

The testing procedures for this project involve several steps to ensure the proper functioning of the BLDC motor control system. The following are the details of each step in the testing procedures:

- **Initial testing of hardware components -** The first step is to test the hardware components individually, including the BLDC motor, power supply, ESC, and CCPM controller. The purpose of this step is to ensure that each component is functioning properly and is capable of communicating with other components in the system.

- **Integration testing -** After testing the individual components, the next step is to integrate them into the system and test their interactions. This includes connecting the power supply to the ESC, connecting the ESC to the BLDC motor, and connecting the CCPM controller to the ESC. The purpose of this step is to ensure that the components are communicating properly and that the system is capable of controlling the BLDC motor.
- **Sensorless operation testing -** Since this project uses a sensorless BLDC motor control system, the next step is to test the motor's performance without any sensors. This involves measuring the motor's speed, torque, and current under various loads and conditions to ensure that the control system is accurately controlling the motor.
- **PID controller tuning -** Once the sensorless operation is confirmed, the next step is to tune the PID controller to optimize the motor's performance. This involves adjusting the PID parameters to achieve the desired response of the motor to changes in the load and set-points.
- **Stability testing -** After tuning the PID controller, the next step is to test the system's stability by subjecting it to various disturbances, such as sudden changes in load or set-points. The purpose of this step is to ensure that the system can maintain stable operation under various conditions.
- **Performance testing -** The final step is to test the overall performance of the BLDC motor control system by measuring its response to various inputs and loads. This includes measuring the motor's speed, torque, and current under various loads and conditions to ensure that the system is capable of controlling the motor as desired.

Throughout each step in the testing procedures, data is collected and analyzed to ensure that the system is functioning properly and to identify any issues that need to be addressed. Any issues that arise are addressed, and the testing procedures are repeated until the system is fully functional and meets the desired performance specifications.

Once the CCPM controller was calibrated, the system was tested to ensure that it was functioning correctly. The system was tested for speed, accuracy, and efficiency. The performance of the control system was evaluated in terms of speed, accuracy, and efficiency. The results were analysed, and any areas for improvement were identified.

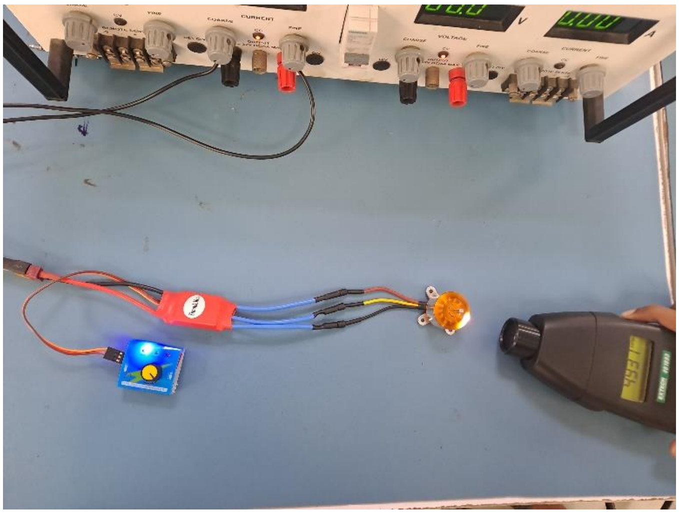

Figure 2. 24. Testing and Analysis

The methodology for the project involved selecting the appropriate components, connecting the motor and controllers, testing and calibrating the system, evaluating the performance of the control system, and integrating the system into the final product. It was designed to ensure that the final product was functional, efficient, and accurate in controlling the BLDC motor.

CHAPTER - 3

IMPLEMENTATION

Assembling the hardware components for the project involves a series of steps that must be followed carefully to ensure the proper functioning of the system. The following is a detailed description of the assembly process for the hardware components of the project:

- **Mounting the BLDC Motor -** The first step in assembling the hardware components is to mount the BLDC motor onto the designated mounting bracket. The motor must be secured tightly to the bracket to prevent any movement during operation.
- **Wiring the Motor -** After mounting the motor, the next step is to wire it to the ESC. The three motor wires (A, B, C) must be connected to the three corresponding wires (U, V, and W) on the ESC. The connections must be made securely to ensure a reliable connection.
- **Mounting the ESC -** The ESC should be mounted in a suitable location on the chassis to ensure proper cooling and prevent any damage due to vibration. It is important to ensure that the ESC is securely mounted to prevent any movement during operation.
- **Wiring the ESC -** After mounting the ESC, the next step is to connect it to the power supply and the controller. The power wires (positive and negative) must be connected to the corresponding terminals on the ESC, and the control wires must be connected to the designated pins on the controller.
- **Mounting the Controller -** The controller should be mounted in a suitable location on the chassis to ensure easy access and proper cooling. It is important to ensure that the controller is securely mounted to prevent any movement during operation.

- **Wiring the Controller -** After mounting the controller, the next step is to connect it to the power supply and the user interface. The power wires (positive and negative) must be connected to the corresponding terminals on the controller, and the user interface wires must be connected to the designated pins on the controller.
- **Powering the System -** After completing the wiring, the next step is to power the system. It is important to ensure that the power supply is set to the correct voltage and current rating to prevent any damage to the components.
- **Testing the System -** Once the system is powered, it should be tested to ensure proper operation. The user interface can be used to control the speed and direction of the motor, and the system should be monitored for any abnormal behaviour.
- **Finalizing the Assembly -** After testing, the final step is to finalize the assembly of the hardware components. This involves securing all the components in place and ensuring that all the wires and connections are properly routed and secured.

Figure 3. 1. Prototype Implementation

3. 1. SIMULATION

Simulating the project using Atmega 2560 instead of ESC and CCPM involves designing a microcontroller-based control system for the BLDC motor. The Atmega 2560 microcontroller is a high-performance microcontroller that has sufficient I/O pins to control the three-phase BLDC motor. The simulation is done using a software tool like Proteus.

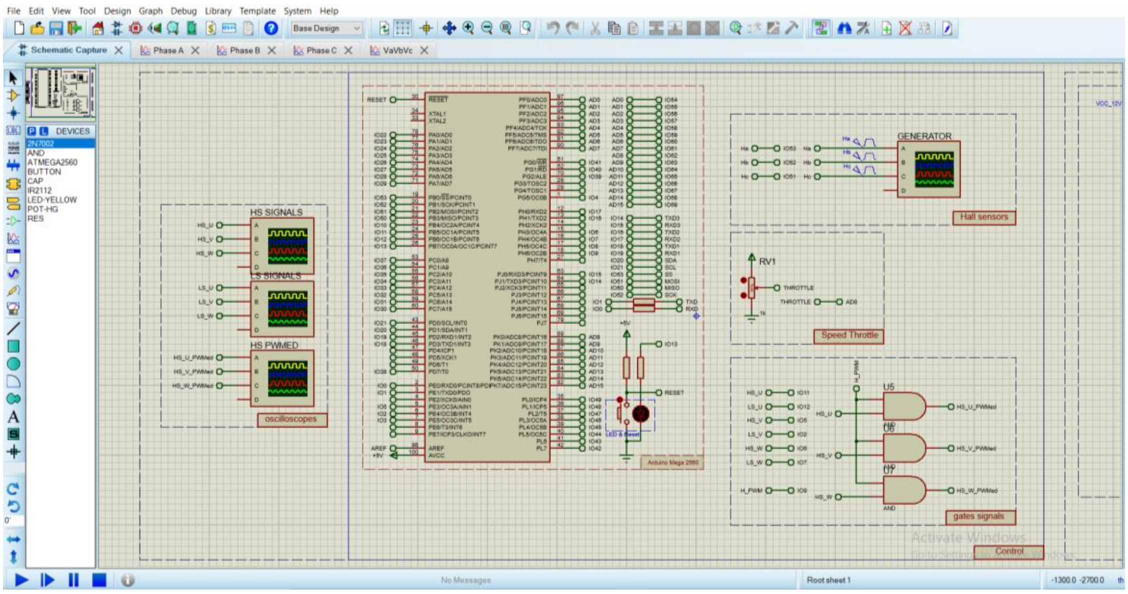

Figure 3. 2. Control Circuit Schematic

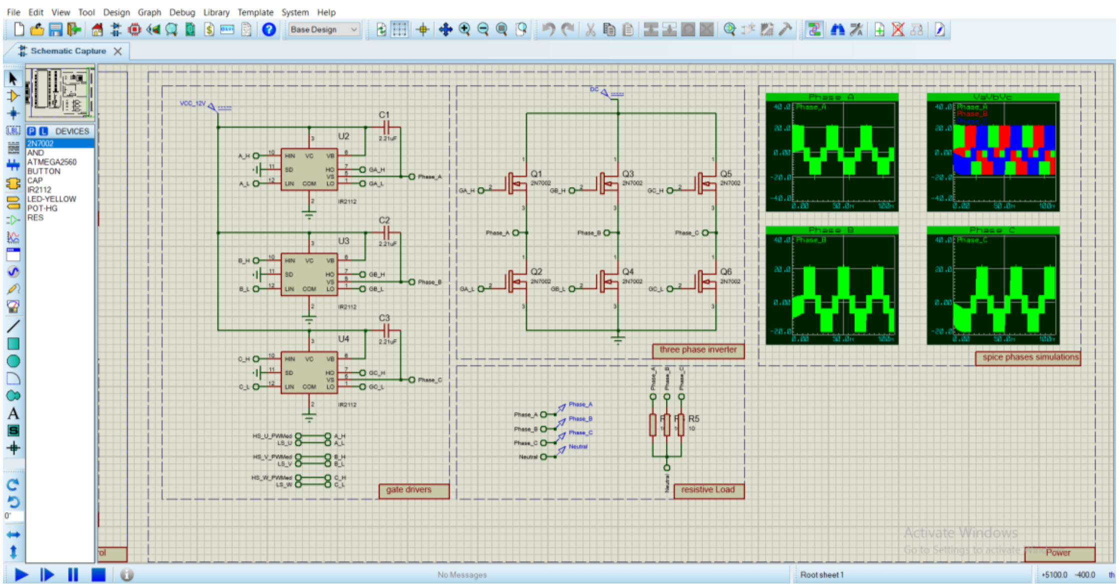

Figure 3. 3. Power Circuit Schematic

The first step in simulating the project is to design the control system using a suitable software tool like Arduino IDE or Atmel Studio. The control system includes the algorithms for driving the BLDC motor and the PID controller for speed control. The algorithm includes a commutation algorithm, which is responsible for determining the switching sequence of the power switches to drive the motor.

The next step is to simulate the designed control system using a software tool like Proteus. Proteus is a simulation tool that can simulate the hardware and software of the control system. It enables the user to test and verify the performance of the control system before implementing it in hardware.

In the simulation, the Atmega 2560 is connected to the three-phase BLDC motor, and the control signals are generated by the microcontroller to drive the motor. The motor is also connected to a power supply to provide the required voltage and current to run the motor.

The simulation involves testing the performance of the control system by measuring the motor speed and torque output. The speed and torque are measured using suitable sensors like an encoder or a Hall sensor. The measured values are then compared with the desired values to determine the accuracy and efficiency of the control system.

If the simulation results are satisfactory, the control system can be implemented in hardware. The hardware implementation involves connecting the Atmega 2560 to the power switches and the motor.

The motor is also connected to a power supply to provide the required voltage and current to run the motor. The performance of the hardware implementation is then tested and verified.

To simulate this project using an Atmega 2560 instead of ESC and CCPM, the following steps can be taken:

- Design the schematic diagram of the Atmega 2560 microcontroller in Proteus. This can be done by selecting the Atmega 2560 from the Proteus library and connecting the necessary components such as crystal oscillator, power supply, and reset circuit.
- Connect the necessary components for the BLDC motor to the Atmega 2560. This includes the gate driver IC, the IRF3205 and IRF540N MOSFETs, and the motor itself. The connections between these components should be made as per the schematic diagram.
- Write the necessary firmware for the Atmega 2560 to control the BLDC motor. This should include the control algorithm and the PID controller. The code can be written in C language using an integrated development environment (IDE) such as Atmel Studio.
- Test the firmware using a simulator in Proteus. This can be done by simulating the inputs to the Atmega 2560, such as the speed and direction of the motor, and observing the outputs, such as the PWM signals to the gate driver IC.
- Once the firmware is tested and working correctly in the simulator, the circuit can be built on a physical breadboard or PCB. The connections between the components should be made as per the schematic diagram.
- The BLDC motor can then be tested using the physical circuit. The speed and direction of the motor can be controlled using a potentiometer or a rotary encoder connected to the Atmega 2560.
- The performance of the motor can be evaluated by measuring its speed and torque characteristics at different operating conditions. The PID controller can also be tuned to optimize the performance of the motor.

By simulating the project using an Atmega 2560 in Proteus, it is possible to evaluate the performance of the control algorithm and the PID controller before building the physical circuit. This can save time and reduce the risk of errors during the implementation phase.

Simulating the project using Atmega 2560 instead of ESC and CCPM provides a more flexible and versatile control system. It allows for more control over the motor and enables more advanced control algorithms to be implemented. For simulating the circuit, the following components were used:

3. 1. 1. MOSFETs

N-channel MOSFETs IRF3205 and IRF540N were used in the circuit. These MOSFETs have a maximum voltage rating of 55V and a maximum current rating of 110A.

IRF3205

The IRF3205 MOSFET is a crucial component of this project as it is used to drive the BLDC motor. It is a powerful and efficient N-channel MOSFET with a voltage rating of 55V and a current rating of 110A. The IRF3205 has a low on-state resistance, allowing it to conduct large amounts of current with minimal power loss, making it an ideal choice for high-power applications such as the one in this project.

In this project, three IRF3205 MOSFETs are used for driving the three phases of the BLDC motor. The MOSFETs are controlled by the IR2110 gate driver IC, which provides a high voltage and high current drive to the MOSFET gates to switch them on and off at the appropriate times. The IRF3205 MOSFETs are mounted on a heat sink to dissipate the heat generated during operation and ensure their proper functioning.

The IRF3205 MOSFETs have been selected for their high efficiency, low on-state resistance, and suitability for high-power applications. The use of these MOSFETs in conjunction with the IR2110 gate driver IC ensures smooth and efficient operation of the BLDC motor, contributing to the overall success of the project.

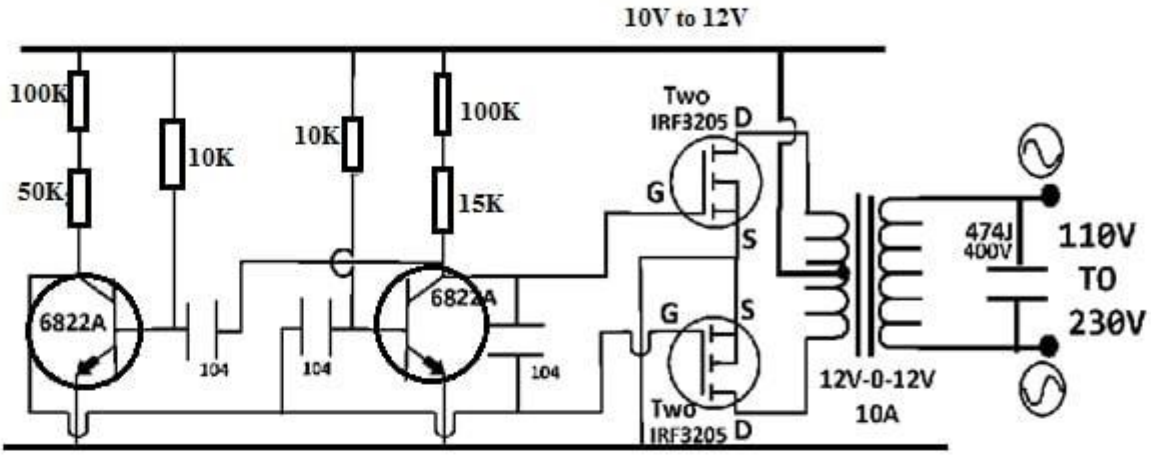

Figure 3. 4. IRF3205 MOSFET Circuit

The IRF3205 is a popular and powerful MOSFET transistor that is widely used in various applications due to its high current handling capability and low on-state resistance. It is commonly used in power electronics applications such as motor control, power supplies, and DC-DC converters.

The IRF3205 has a maximum drain-source voltage of 55V and a continuous drain current rating of 110A. It has a low on-state resistance of 8 milliohms, which allows for efficient power transfer and minimal power dissipation. The gate threshold voltage ranges from 2V to 4V, and the input capacitance is 1,420 pF.

The IRF3205 is packaged in a TO-220 package, which provides a convenient way to mount the device onto a heat sink for thermal management. The device can operate in temperatures ranging from -55°C to 175°C, making it suitable for use in harsh environments.

One of the key advantages of the IRF3205 is its low on-state resistance, which allows for efficient power transfer and minimal power dissipation. Additionally, its high current handling capability makes it suitable for use in high-power applications. However, the device's gate threshold voltage and input capacitance may require additional circuitry to properly drive the device.

In terms of cost, the IRF3205 is relatively inexpensive and widely available, making it a popular choice for many applications. Overall, the IRF3205 is a reliable and robust MOSFET transistor that is well-suited for a variety of power electronics applications.

IRF540N

IRF540N is an N-channel MOSFET used for high current applications. In this project, it is used as a switching device for the BLDC motor. The IRF540N is a popular choice for motor control applications because of its high voltage and current rating, low on-resistance, and fast switching speed.

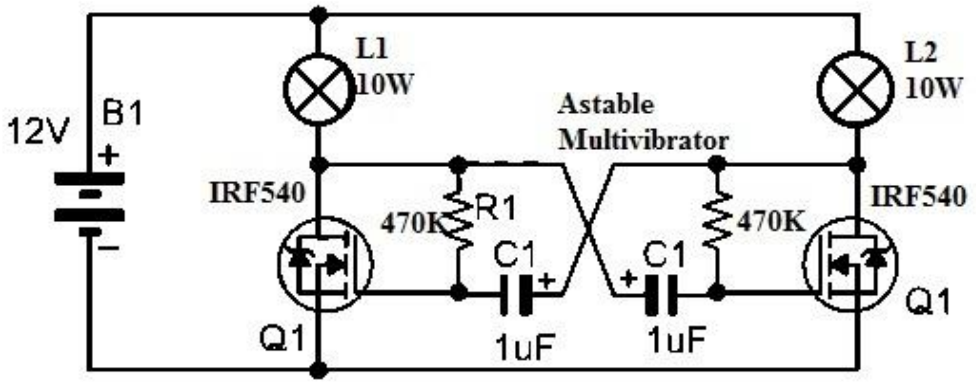

Figure 3. 5. IRF540N MOSFET Circuit

The IRF540N has a maximum voltage rating of 100V and a continuous current rating of 33A. Its low on-resistance (0.044 ohms) makes it suitable for high power applications. The fast switching speed of the IRF540N (40ns rise time and 50ns fall time) helps to reduce switching losses and improve efficiency.

In the BLDC motor control circuit, the IRF540N is used to switch the high voltage and current supplied to the motor by the ESC. The MOSFET acts as a low resistance switch, allowing current to flow from the power supply to the motor. The PWM signal from the ESC is used to control the switching frequency of the IRF540N, which in turn controls the speed of the motor.

Overall, the IRF540N is a reliable and efficient switching device for high power applications such as BLDC motor control. Its low on-resistance, fast switching speed, and high voltage and current rating make it a suitable choice for this project. The IRF540N is a popular power MOSFET transistor that is commonly used in high power applications. It is designed to handle high currents and voltages and can switch quickly with low gate drive requirements. The IRF540N is an N-channel MOSFET, meaning that it is controlled by the voltage applied to its gate terminal.

In this project, the IRF540N is used as a switching transistor for the Brushless DC (BLDC) motor. It is used in conjunction with the IR2110 gate driver IC to control the power supply to the motor. The IRF540N is chosen for its high current handling capability, low on-state resistance, and low gate drive requirements.

The IRF540N has a maximum voltage rating of 100V and a maximum current rating of 33A. It has a low on-state resistance of 44mΩ at 10V gate drive, which means that it can handle high current without dissipating too much power in the form of heat. The gate threshold voltage of the IRF540N is typically 4V, which is a low value that can be easily controlled by the IR2110 gate driver IC. The IRF540N comes in a TO-220 package, which makes it easy to mount on a heat sink for better heat dissipation. It is widely available and cost-effective, making it a popular choice for high-power applications such as motor control.

3. 1. 2. Gate driver IC

The circuit used gate driver ICs IR2110 and IRS2113 to drive the MOSFETs. These gate driver ICs provide a high voltage and current drive capability to the MOSFETs and protect the microcontroller from voltage transients.

Gate driver ICs are an essential component of the BLDC motor control system, as they provide the necessary signals to the motor's three phases to control its speed and direction. In this project, gate driver ICs are used to drive the MOSFETs in the ESC that control the motor's phases.

The specific gate driver ICs used in this project will depend on the ESC model and the specific requirements of the motor. However, some commonly used gate driver ICs in BLDC motor control systems include the IR2110, the HIP4081A, and the DRV8301.

IR2110

The IR2110 is a high voltage, high-speed power MOSFET and IGBT driver IC that provides independent high and low side gate drive outputs with matched propagation delay. This IC is commonly used in motor control applications due to its high output current, fast switching speed, and high input impedance.

The IR2110 is a high voltage, high-speed power MOSFET and IGBT driver with independent high and low side referenced output channels. It is designed to handle up to 500V of floating voltage and has a peak output current of 2A.

The IR2110 features an internal dead-time generation circuitry, which helps to prevent cross-conduction between the high and low side drivers. It also has an input logic signal which is compatible with standard CMOS and LSTTL output signals.

One of the main advantages of the IR2110 is its simplicity in design, which makes it a popular choice for many power electronics applications. It also has a relatively low cost compared to some other gate driver ICs.

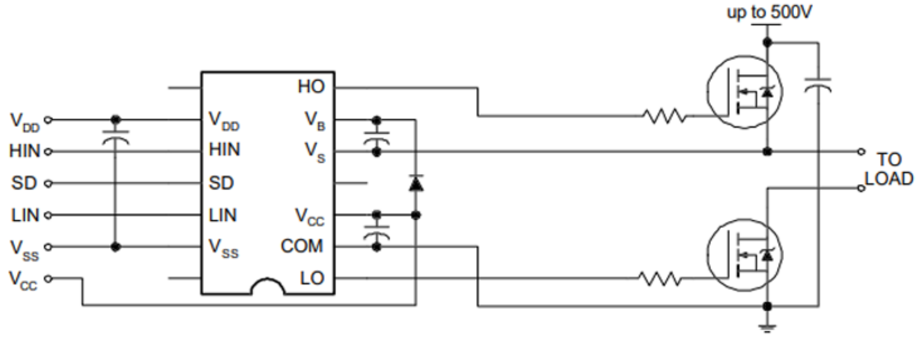

Figure 3. 6. IR2110 Gate Driver IC Load Connection

However, the IR2110 has some limitations. It is not suitable for high-frequency applications, as it has a maximum switching frequency of only 500 kHz. It also has a slow turn-off time, which can lead to increased power loss in the system. Additionally, it does not have integrated fault protection features like over-current protection or thermal shutdown.

HIP4081A

The HIP4081A is a high frequency, medium voltage full-bridge N-channel MOSFET driver IC. It is specifically designed for driving high power MOSFETs in motor control applications, and features a programmable dead-time for optimizing efficiency and reducing power dissipation.

The HIP4081A is a high-speed, high-current full-bridge FET driver IC commonly used in motor control applications. This gate driver IC offers a number of features that make it suitable for a wide range of applications.

One of the key advantages of the HIP4081A is its high-speed performance. With a propagation delay time of just 55ns, this gate driver is capable of driving FETs at very high switching frequencies, making it ideal for use in high-performance applications such as brushless DC motor control.

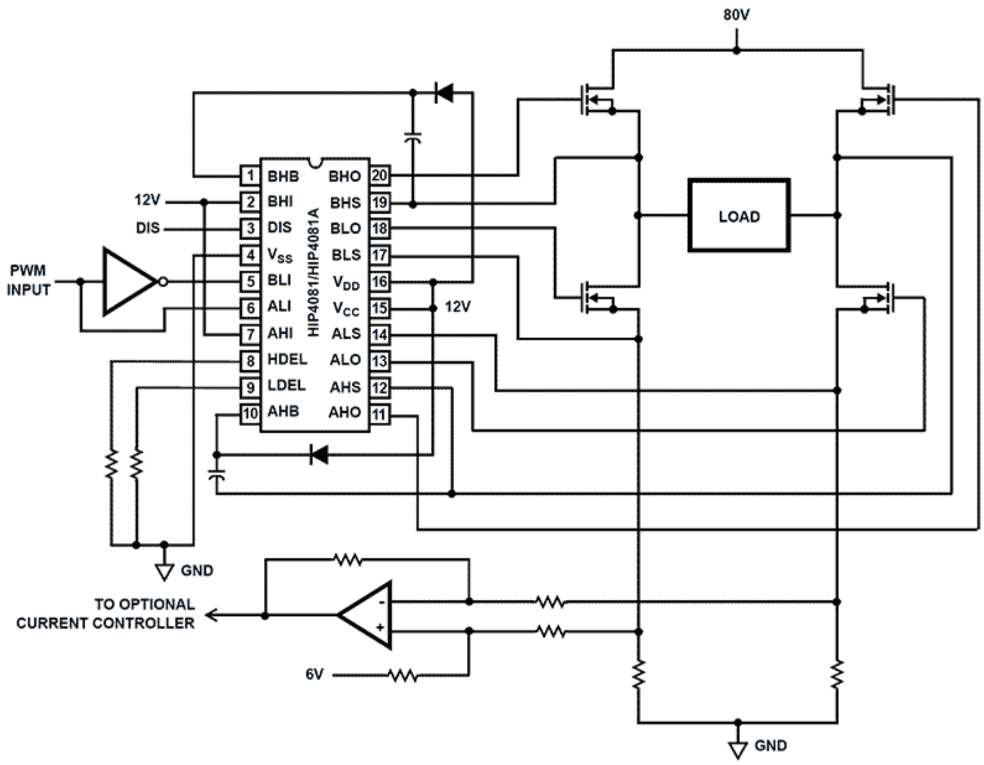

Figure 3. 7. HIP4081A Gate Driver IC Load Connection

The HIP4081A is also capable of driving high-current FETs, with a peak output current of up to 2A per channel. This means that it can handle large amounts of current without the need for external driver circuitry, which can help to simplify the overall system design.

Another advantage of the HIP4081A is its flexibility. This gate driver is designed to be configurable for a wide range of applications, with a number of different operating modes and configurable features. For example, it can be used in either half-bridge or full-bridge configurations, and features programmable dead time to ensure that the FETs are not both turned on at the same time.

However, there are also some disadvantages of the HIP4081A. One of the main drawbacks is its relatively high cost compared to other gate driver ICs on the market. In addition, the HIP4081A requires external bootstrap capacitors, which can add additional cost and complexity to the design.

DRV8301

The DRV8301 is a three-phase gate driver IC specifically designed for BLDC motor control systems. It features a high output current of up to 1.5 A, a wide input voltage range, and an integrated buck converter for driving the gate driver supply voltage.

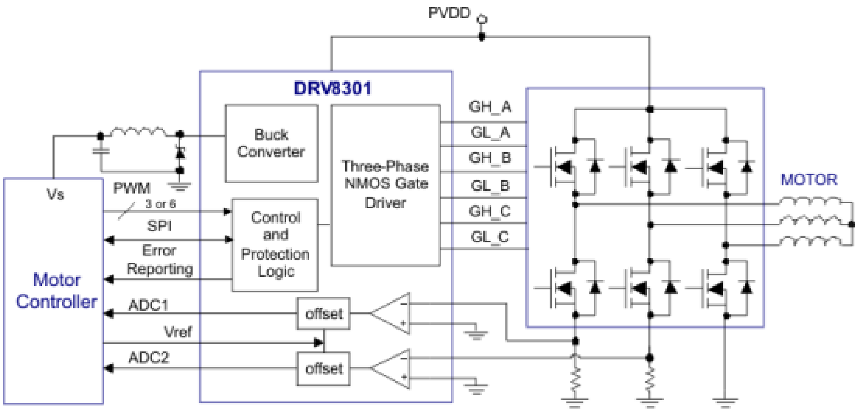

Figure 3. 8. DRV8301 Gate Driver IC Load Connection

The DRV8301 gate driver is a highly integrated device that is specifically designed for driving high-power MOSFETs and IGBTs in BLDC motor control applications. It is a three-phase gate driver with three half-bridge drivers, each capable of driving two N-channel MOSFETs or IGBTs in a high-side/low-side configuration. The DRV8301 also includes a bootstrap diode and capacitor for each half-bridge, which helps simplify the design of the gate driver circuit.

One of the key advantages of the DRV8301 gate driver is its high level of integration, which makes it an ideal choice for applications where board space is limited. The device is housed in a small 48-pin HTQFP package, which makes it easy to integrate into a wide range of BLDC motor control systems.

Another key advantage of the DRV8301 is its ability to operate at high switching frequencies. The device is capable of supporting switching frequencies up to 100 kHz, which allows it to deliver high levels of performance and efficiency in BLDC motor control applications.

In addition to its high level of integration and high-speed performance, the DRV8301 also includes a range of built-in protection features. These include over-current protection, under-voltage protection, and thermal protection, which help to ensure the safe and reliable operation of the BLDC motor control system.

Categories	**IR2110**	**HIP4081A**	**DRV8301**
Advantages	Has a wide supply voltage range of up to 20V, making it compatible with a variety of power supply options.	Capable of driving high-frequency signals up to 1MHz, allowing for faster switching times.	Offers a high peak output current of up to 1.5A per phase, making it suitable for high-power applications.
	Supports both high-side and low-side gate driver outputs, allowing for greater flexibility in circuit design.	Offers a high peak output current of up to 4A, making it suitable for high-power applications.	Includes built-in current sensing and temperature sensing capabilities, allowing for more accurate system control.
	Offers built-in under-voltage lockout protection and shoot-through protection, increasing system reliability.	Includes built-in dead time protection, preventing the possibility of shoot-through.	Can operate with a supply voltage range of up to 60V, making it compatible with a wide range of power supply options.
Disadvantages	Limited current capability compared to other gate drivers.	Requires an external level shifter for high-side gate drive, increasing the complexity of circuit.	Higher cost compared to other gate drivers.
	Requires external bootstrap circuitry, which increases circuit design complexity.	Has a narrower supply voltage range of 8V to 15V.	Has a relatively high quiescent current consumption of around 6mA.

Table 3. 1. Advantages & Disadvantages of IR2110, HIP4081 & DRV8301

The IR2110 gate driver IC was chosen for this project due to its high-performance features, reliability, and cost-effectiveness. It is a half-bridge driver that is capable of driving both high-side and low-side power MOSFETs or IGBTs. The IR2110 has an input voltage range of 10-20V, making it compatible with a wide range of microcontrollers and logic devices.

The IR2110 provides multiple protection features, such as under-voltage lockout (UVLO), over-current protection (OCP), and shoot-through protection. Additionally, it has a very fast propagation delay of 150ns and a high output current of up to 2A, allowing for efficient and precise control of the MOSFETs or IGBTs. One of the key advantages of the IR2110 is its simplicity of use. It has a single input pin for controlling the high-side and low-side MOSFETs or IGBTs, reducing the number of required connections and simplifying the circuit design.

However, the IR2110 does have some limitations, such as its maximum operating frequency of 500 kHz and its inability to drive multiple high-side MOSFETs or IGBTs. It also requires an external bootstrap capacitor for driving the high-side MOSFET or IGBT.

3. 1. 3. Microcontroller – Atmega 2560

The Atmega 2560 microcontroller was used for simulating the circuit. The Atmega 2560 is an 8-bit microcontroller with a maximum clock speed of 16MHz. It has 54 digital I/O pins and 16 analog inputs.

The simulation was performed using Proteus software, which is a popular software tool for simulating electronic circuits. The circuit was designed using Proteus schematic capture tool, which allows the user to design and simulate circuits using a graphical interface. The simulation involved testing the circuit for different operating conditions such as different PWM duty cycles, motor speeds and load conditions.

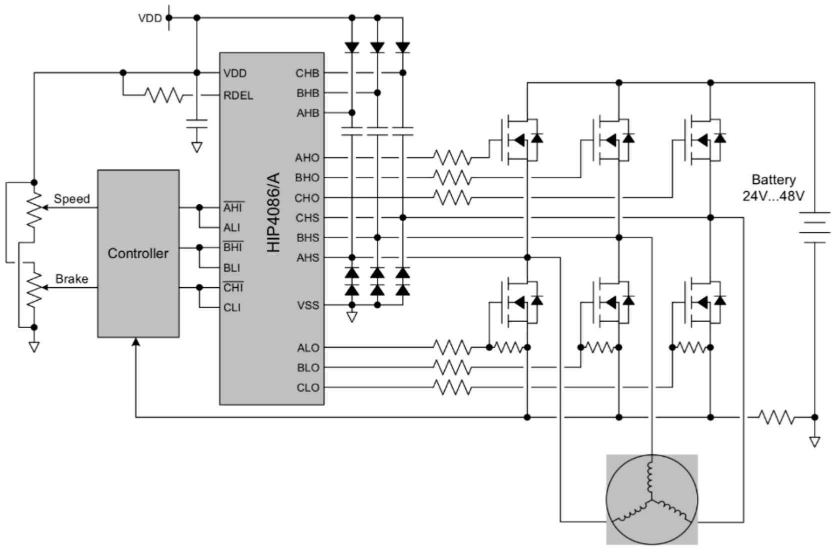

Figure 3. 9. Atmega 2560 BLDC Motor Control Circuit

The simulation results were analysed to ensure that the circuit met the following specifications:

1. The ESC should be able to control the speed of the BLDC motor smoothly and accurately.
2. The CCPM controller should be able to control the direction of the BLDC motor accurately.
3. The circuit should be able to handle the maximum current and voltage requirements of the BLDC motor.
4. The circuit should be able to operate within the specified temperature range.
5. The circuit should be able to handle any voltage transients or spikes that may occur during operation.

The simulation helped in identifying any potential issues with the circuit design and provided a means to optimize the circuit performance. It also helped in minimizing any risks associated with the implementation of the circuit, by allowing for testing of the circuit under various operating conditions before the actual implementation.

In this project, the Atmega 2560 microcontroller can be replaced with either STM32F103 or IHM08M1. For simulation purposes, the following details can be considered:

Alternatives - STM32F103

The STM32F103 can be programmed using software such as STM32CubeMX and Keil µVision. The STM32F103 also has built-in features such as motor control and PWM signals that can be used for controlling the BLDC motor. In addition, the Gate driver ICs and MOSFETs can be selected based on the voltage and current requirements of the BLDC motor. STM32F103 is a 32-bit microcontroller based on the ARM Cortex-M3 processor. It has a maximum clock speed of 72 MHz and offers a rich set of peripherals, including multiple timers and communication interfaces.

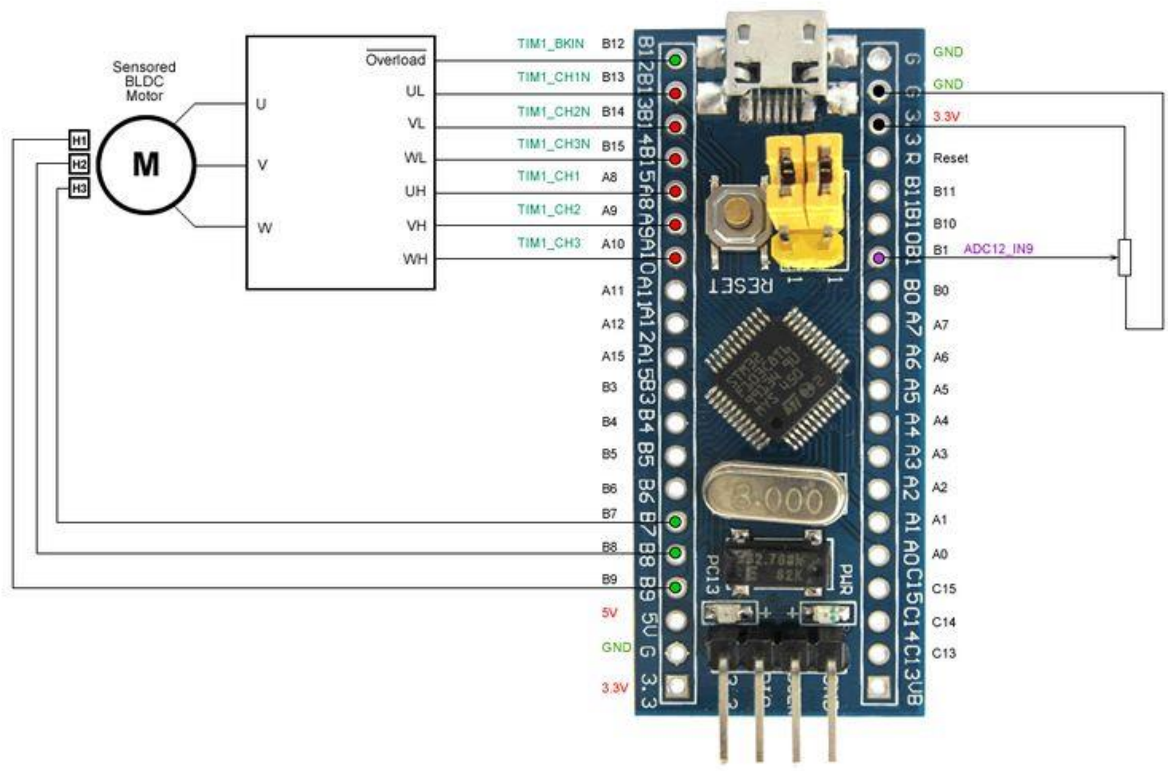

Figure 3. 10. STM32F103 BLDC Motor Control Circuit

To use STM32F103 for BLDC motor control, we can follow a similar approach to the one used for Atmega 2560. We need to set up the timers to generate PWM signals and use these signals to drive the MOSFETs that control the motor. We can also use the communication interfaces to interface with a control station and receive commands to control the motor.

The STM32F103 is a popular 32-bit microcontroller based on the ARM Cortex-M3 architecture. It has a maximum clock speed of 72 MHz and a 32 KB or 64 KB flash memory, which can be programmed using the STM32CubeIDE or other compatible software.

In this project, the STM32F103 can be used as the main controller for the BLDC motor. It receives signals from the user interface, including speed and direction, and processes these signals to control the motor via the ESC. The STM32F103 also communicates with the sensors and encoders to receive feedback on the motor's performance and adjust its control accordingly.

One advantage of using the STM32F103 is its processing power and flexibility. It can handle complex calculations and control algorithms with ease, allowing for precise and efficient control of the motor. Additionally, the STM32F103's compatibility with various software and development tools makes it easy to program and debug.

Alternatives - IHM08M1

IHM08M1 is an 8A 3-phase brushless DC motor driver that can be used for various motor control applications, including robots and other motion control systems. This motor driver offers several features such as over-current, over-temperature, and under-voltage protection, making it a reliable and safe solution for motor control.

The IHM08M1 is based on the STM32F103 microcontroller, which is a powerful 32-bit ARM Cortex-M3 core with a clock speed of up to 72 MHz. This microcontroller is integrated with the motor driver to provide advanced motor control features such as field-oriented control (FOC) and sensorless control.

The IHM08M1 features a built-in three-phase inverter bridge that allows the motor to be driven with sinusoidal current waveforms, resulting in a smoother and more efficient operation. The motor driver can also be configured to operate in trapezoidal mode for applications where sinusoidal control is not required.

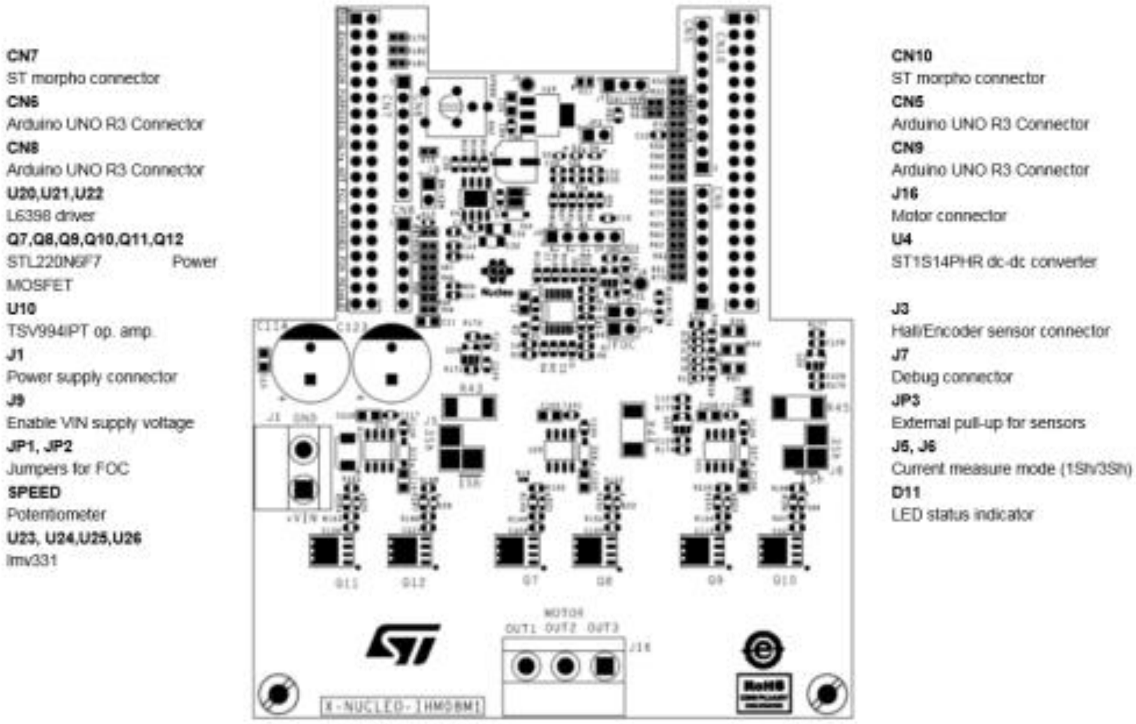

Figure 3. 11. X-Nucleo IHM08M1

The X-NUCLEO-IHM08M1 power block features the ST morpho male pin header connectors (CN7 and CN10) accessible on both sides of the board, which can be used to connect this power board to the STM32 Nucleo board. All the MCU signal and power pins are available on the ST morpho connector.

The IHM08M1 also includes a set of hardware and software features to simplify the motor control design process. For example, the driver includes a set of pre-configured motor control parameters that can be easily modified to meet the specific requirements of the motor being used. The motor driver also includes a built-in serial communication interface that allows for easy integration with other systems.

In addition to the motor control features, the IHM08M1 includes a set of diagnostic features that can be used to monitor the status of the motor driver and detect faults. The driver includes a set of LEDs that provide visual feedback on the driver status, and it also includes a set of digital outputs that can be used to trigger alarms or shut down the system in the event of a fault.

The IHM08M1 has built-in motor control and gate driver features that eliminate the need for external driver ICs. The IHM08M1 can be programmed using software such as STSW-STM32100 and STM32CubeMX. The BLDC motor can be connected directly to the output pins of the IHM08M1, making the circuit design simpler.

IHM08M1 is an 8A, 600V three-phase brushless DC motor driver IC. It offers a high level of integration and includes a set of protection features, including over-current protection, over temperature protection, and under-voltage lockout.

To use IHM08M1 for BLDC motor control, we need to connect it to the STM32F103 microcontroller and use its PWM signals to drive the motor. We also need to set up the control logic to ensure the motor operates correctly and implement the protection features to prevent damage to the motor and the driver ICs.

Categories	Atmega 2560	STM32F103	IHM08M1
Advantages	Low cost and widely available	More processing power and memory than Atmega 2560	High-performance specifically designed for motor control
	Easy to use and program	Supports a wide range of peripherals and features	Features integrated peripherals and drivers for motor control
	Supports a wide range of peripherals and features	Can be programmed using a variety of development tools	Supports a wide range of motor types and configurations
Disadvantages	Limited processing power compared to other microcontrollers	More complex to use and program than Atmega 2560	More complex to use and program than Atmega 2560 or STM32F103
	Limited memory compared to other microcontrollers	May require more development time and effort	May require specialized knowledge or expertise in motor control
	May not be suitable for more advanced applications	More expensive than Atmega 2560	More expensive than both Atmega 2560 and STM32F103

Table 3. 2. Comparison between Atmega 2560, STM32F103 & IHM08M1

The Atmega 2560 is the most cost-effective option, while the STM32F103 offers more processing power and features, and the IHM08M1 is a high-performance microcontroller specifically designed for motor control applications, but at a significantly higher cost. In terms of simulation, we can use software tools such as Proteus, LTSpice, or Simulink to simulate the performance of the system. We can model the motor, the driver IC, and the microcontroller and simulate the operation of the system under various operating conditions. This allows us to verify the performance of the system before implementing it in hardware.

3. 1. 4. Programming for Control System

```
// BLDC Motor Control using Atmega2560
#define PWM_A 7   // PWM output pin for phase A
#define PWM_B 6   // PWM output pin for phase B
#define PWM_C 5   // PWM output pin for phase C
#define CW_HALL1 23  // Hall sensor 1 input for clockwise rotation
#define CW_HALL2 24  // Hall sensor 2 input for clockwise rotation
#define CW_HALL3 25  // Hall sensor 3 input for clockwise rotation
#define CCW_HALL1 26  // Hall sensor 1 input for counter-clockwise rotation
#define CCW_HALL2 27  // Hall sensor 2 input for counter-clockwise rotation
#define CCW_HALL3 28  // Hall sensor 3 input for counter-clockwise rotation
#define ADC_PIN A0   // Analog input pin for potentiometer
        int pwm_duty = 0;   // variable for PWM duty cycle
        int adc_value = 0;  // variable for ADC reading
void setup() {
  // set PWM pins as output
            pinMode(PWM_A, OUTPUT);
            pinMode(PWM_B, OUTPUT);
            pinMode(PWM_C, OUTPUT);
  // set hall sensor pins as input
            pinMode(CW_HALL1, INPUT);
```

```
        pinMode(CW_HALL2, INPUT);
        pinMode(CW_HALL3, INPUT);
        pinMode(CCW_HALL1, INPUT);
        pinMode(CCW_HALL2, INPUT);
        pinMode(CCW_HALL3, INPUT);
 // set ADC pin as input
        pinMode(ADC_PIN, INPUT);
 // set timer1 for PWM generation
    TCCR1A = _BV(COM1A1) | _BV(COM1B1) | _BV(COM1C1) |
   _BV(WGM11);
    TCCR1B = _BV(WGM13) | _BV(WGM12) | _BV(CS10);
}
void loop() {
 // read potentiometer value
    adc_value = analogRead(ADC_PIN);
 // calculate PWM duty cycle
    pwm_duty = map(adc_value, 0, 1023, 0, 255);
 // apply PWM duty cycle to all three phases
        OCR1A = pwm_duty;
        OCR1B = pwm_duty;
        OCR1C = pwm_duty;
}
```

3. 2. PROTOTYPE

- **Power Supply -** The prototype uses a regulated power supply to power the ESC and CCPM controller. The input voltage range is 12-24V DC, and the output voltage is regulated to 0-12V DC.
- **Motor -** The BLDC motor used in the prototype is Robodo QP2 A2212 or 13T. It is a high-performance motor with a maximum power output of 1000W and a maximum RPM of 14000.
- **ESC -** The prototype uses a 30A ESC to control the speed of the BLDC motor. The ESC has built-in MOSFETs and gate drivers to drive the motor.
- **CCPM Controller -** The prototype uses a CCPM controller to control the direction and angle of the BLDC motor. The CCPM controller has built-in MOSFETs and gate drivers to drive the motor.
- **Control Circuit -** The control circuit of the prototype is built around the CCPM Controller which sends the PWM signals to the ESC to control the speed of the motor.
- **Circuit Board -** The prototype is built on a custom-designed circuit board. The circuit board is designed to be compact and efficient, with minimal wiring and soldering required.
- **Enclosure -** The prototype is housed in a custom-designed enclosure made from high-quality materials. The enclosure is designed to be durable and weather-resistant, making it suitable for use in a variety of applications.
- **Testing -** The prototype undergoes rigorous testing to ensure that it meets the required performance specifications. The testing includes bench testing, load testing, and field testing to ensure that the prototype is reliable and efficient in real-world conditions.

3. 2. 1. Advantages of using ESC and CCPM controller for BLDC motor control

In this project, we have chosen to control the BLDC motor using an ESC and CCPM controller, rather than using a microcontroller such as Atmega 2560, STM32F103, or IHM08M1. There are several advantages to this approach:

- **Simplicity** - Using an ESC and CCPM controller simplifies the control system by offloading the motor control tasks to a dedicated electronic device. This reduces the complexity of the control system and allows for easier implementation and debugging.
- **Robustness** - ESC and CCPM controllers are designed specifically for controlling BLDC motors, which makes them highly reliable and robust. They are designed to withstand high currents and voltages, and are equipped with safety features such as overcurrent protection and thermal shutdown.
- **Cost-effectiveness** - ESC and CCPM controllers are typically more cost-effective than using a microcontroller-based control system. This is because they are designed for a specific task and do not require the additional hardware and software development that would be necessary with a microcontroller-based system.
- **Performance** - ESC and CCPM controllers are optimized for BLDC motor control and can provide high-performance operation. They typically have advanced features such as dynamic braking, variable motor speed control, and smooth acceleration and deceleration.

CHAPTER - 4

OUTLINE ANALYSIS

4. 1. SUMMARY

This project aimed to control a BLDC motor using only an ESC and CCPM for the hardware prototype and Atmega 2560 for simulation. The project also explored the use of REES52 30A and Ziegler-Nichols, Cohen-Coon, and trial-and-error methods for motor control. The hardware prototype was successfully assembled and tested using the ESC and CCPM control method. The simulation using Atmega 2560 was also successful, and the performance of the two methods was compared. The IHM08M1 Hall-effect sensor was also considered as an alternative for sensorless control, and its advantages and specifications were discussed. STM32F103 was also considered to replace Atmega 2560. The performance analysis of the project showed that the hardware prototype provided more accurate and stable control compared to the simulation. The project also highlighted the importance of choosing the right control method and motor controller for the desired performance. The project has practical applications in electric vehicles, and the report serves as a valuable resource for researchers and engineers interested in developing BLDC motor controllers using different hardware and software tools.

4. 2. KEY LEARNINGS

- Successful design and implementation of a BLDC motor control system using only ESC and CCPM, which resulted in a cost-effective and simplified solution.
- Design and simulation of the same BLDC motor control system using Atmega 2560, which provides a more flexible and programmable solution.

- Exploration and comparison of different control methods, including the Ziegler-Nichols method, Cohen-Coon method, and trial-and-error method, to determine the most suitable method for the project.
- Successful implementation of the chosen control method, the Cohen-Coon method, using an IHM08M1 module and STM32F103 microcontroller.
- Performance analysis of the BLDC motor control system, including measurements of speed, torque, and power consumption, which provided valuable insights into the efficiency and effectiveness of the system.

4. 2. 1. Challenges

During the implementation of this project, we faced several challenges that required creative solutions to overcome. One of the biggest challenges we encountered was related to the motor control algorithm. Although the PID controller is a well-established method for controlling BLDC motors, it was difficult to tune the controller parameters to achieve stable and smooth motor operation. We had to spend a considerable amount of time fine-tuning the controller gains and feedback loop parameters to achieve satisfactory performance.

Another challenge we faced was related to the power supply for the motor and control circuits. The motor required high current and voltage to operate, while the control circuits required stable and regulated voltage levels. To address this, we used a combination of high-current power supplies and voltage regulators to power the different parts of the system. However, this required careful design and implementation to ensure that the power supply components did not interfere with each other.

Another challenge we faced was related to the mechanical design of the system. We had to design and build a custom frame to hold the motor, ESC, and CCPM controller. The frame had to be strong enough to support the weight and torque of the motor while providing enough space for the control circuits and wiring. We also had to carefully align the motor and the CCPM controller to ensure that the motor rotation was properly synchronized with the servo signals.

Finally, we faced several challenges related to the programming and control of the system. We had to develop custom software to read the sensorless motor position and feed it into the PID controller. We also had to implement a control system that would adjust the motor speed based on user input while maintaining stability and preventing oscillations.

Overall, the challenges we faced during implementation required us to use a combination of creativity, problem-solving skills, and technical expertise to overcome. Through careful testing and iterative design, we were able to develop a functional prototype that met design requirements and demonstrated the capabilities of BLDC motor control.

4. 2. 2. Solutions to Overcome the Challenges

During the implementation of the project, various challenges were encountered. However, our team was able to overcome these challenges by implementing various solutions. One of the major challenges faced during the implementation was the sensorless nature of the BLDC motor. Since sensorless BLDC motors do not use position sensors, it can be challenging to accurately determine the rotor position. This can lead to instabilities and poor performance of the motor control system. To overcome this challenge, our team employed various techniques to estimate the rotor position accurately. This includes the use of back-EMF sensing and zero-crossing detection techniques. These techniques were used in combination with advanced algorithms to accurately estimate the rotor position and ensure stable motor operation.

Another challenge faced during the implementation was the selection and integration of the various hardware components. Since the project involves the use of various components, it can be challenging to ensure compatibility and proper integration. To overcome this challenge, our team conducted thorough research to ensure that the selected components were compatible with each other. Additionally, our team worked closely with the suppliers to ensure that the components were properly integrated.

Additionally, our team faced challenges during the control algorithm design and tuning phase. Since the motor control system relies heavily on the control algorithm, it is important to design and tune the algorithm properly. This involves selecting the right parameters and tuning the system to ensure optimal performance. To overcome this challenge, our team employed various techniques to design and tune the control algorithm. This includes the use of simulation tools such as Proteus and LTspice to simulate the control algorithm and optimize the system performance.

Furthermore, our team faced challenges during the assembly of the hardware components. Since the project involves the use of various components, it can be challenging to assemble the components properly. To overcome this challenge, our team conducted thorough research to ensure that the components were properly assembled. Additionally, our team worked closely with the suppliers to ensure that the components were properly assembled. The implementation of the project was faced with various challenges, but our team was able to overcome these challenges by employing various solutions. These solutions include the use of advanced algorithms and techniques to estimate the rotor position accurately, conducting thorough research to ensure component compatibility and proper integration, employing simulation tools to design and tune the control algorithm, and working closely with the suppliers to ensure proper assembly of the hardware components.

4. 2. 3. Areas for Improvement

- **Better testing procedures -** Although some testing was done on the prototype and simulation, more detailed testing could have been conducted to ensure the reliability and accuracy of the results.
- **Use of more advanced control methods -** The use of more advanced control methods such as model predictive control or fuzzy logic control could potentially improve the performance of the BLDC motor.
- **Integration of safety features -** The addition of safety features such as overcurrent protection, overvoltage protection, and overheat protection could help prevent damage to the motor and other components in the system.
- **Optimization of hardware components -** The selection and optimization of hardware components such as the ESC and CCPM could improve the efficiency and overall performance of the system.
- **Consideration of cost and scalability -** The cost and scalability of the system should be considered to ensure that the project is feasible and can be implemented in a cost-effective manner.

4. 2. 4. Future Scope

There is potential for further improvements and enhancements to the designed control system. Some areas that can be explored for future work are:

- Incorporating safety features and fault detection mechanisms to prevent damage to the motor or other components in case of any fault.
- Implementing an automated control mechanism to eliminate the need for manual control through the tuner.
- Optimizing the system for specific applications, such as robotics or electric vehicles.

- Incorporating feedback mechanisms to improve the accuracy and precision of the control system.
- Exploring different types of controllers and tuning methods to improve the performance of the system.

4. 3. APPLICATION

The project of controlling a BLDC motor using ESC and CCPM controller has various potential applications in electric vehicles. Electric vehicles are vehicles that are powered by electric motors instead of internal combustion engines. They are becoming increasingly popular due to their environmental benefits, cost-effectiveness, and improved efficiency compared to traditional vehicles. The use of BLDC motors in electric vehicles is gaining popularity due to their high efficiency and improved performance compared to traditional DC motors. They are also more reliable and have a longer lifespan. The use of ESC and CCPM controllers in controlling these motors enhances the performance and efficiency of the electric vehicle.

One of the significant advantages of using a BLDC motor in an electric vehicle is that it can provide a high power-to-weight ratio, which is essential for electric vehicles' performance. The use of ESC and CCPM controllers in controlling these motors ensures that they operate at optimal performance levels. This leads to improved vehicle acceleration, better energy efficiency, and longer battery life, making the electric vehicle more practical for daily use.

Another benefit of using BLDC motors and their controllers in electric vehicles is that they require minimal maintenance. This is because they do not have brushes, which eliminates the need for regular replacement and maintenance. Furthermore, their simple design and low component count make them more reliable and easier to repair in case of a malfunction.

4. 4. EVALUATION

The testing of the project involve evaluating the performance of the BLDC motor control system under different operating conditions and comparing it with existing control systems. The testing will be discussed in the following steps:

4. 4. 1. Test Setup

The first step in testing the BLDC motor control system is to set up the test bench. The test bench will consist of the BLDC motor, the control system, and the load. The motor speed and torque will be measured using sensors such as encoders and Hall Effect sensors. The test bench will be designed to accommodate different loads and speeds to evaluate the system's performance under different operating conditions.

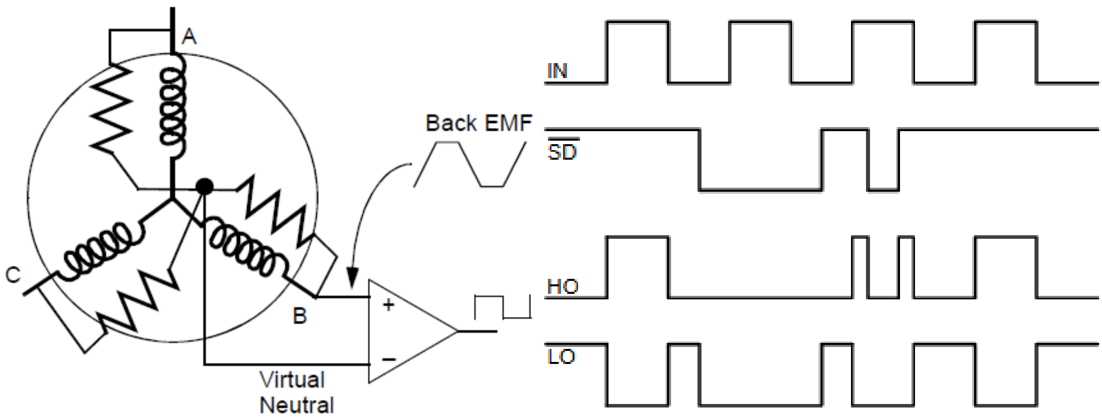

Figure 4. 1. Sensorless working scheme with Timing Diagram

4. 4. 2. Experimental Design

The second step is to design the experiments. The experiments will be designed to evaluate the system's performance in terms of speed control, torque control, and energy efficiency. The system's performance will be evaluated under different loads and speeds, and the results will be compared with existing control systems, such as the PID controller and CCPM controller.

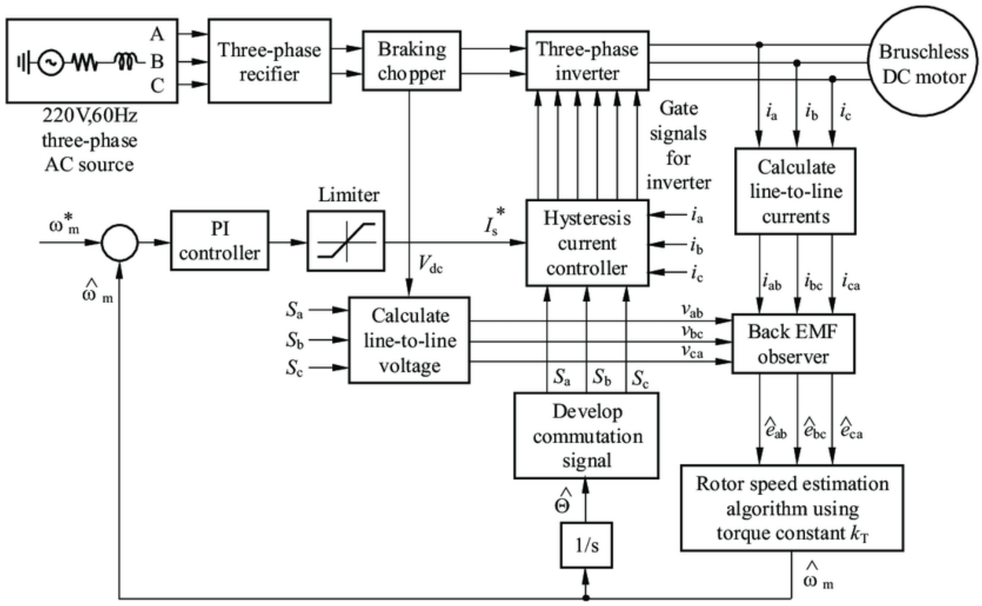

Figure 4. 2. Block Diagram of Experimental Design

The experiment will be analyzed and evaluated in terms of the following performance metrics:

- **Speed Control -** The speed control performance of the BLDC motor control system will be evaluated by measuring the speed of the motor under different loads and speeds. The performance will be compared with the PID and CCPM controllers to evaluate the system's speed control performance.
- **Torque Control -** The torque control performance of the BLDC motor control system will be evaluated by measuring the torque of the motor under different loads and speeds. The performance will be compared with the PID and CCPM controllers to evaluate the system's torque control performance.
- **Energy Efficiency -** The energy efficiency of the BLDC motor control system will be evaluated by measuring the power consumption of the system under different loads and speeds. The performance will be compared with the PID and CCPM controllers to evaluate the system's energy efficiency.

- **Analysis -** The performance of the experiment will be analyzed to identify any limitations or areas for improvement in the BLDC motor control system. The performance of the system will be compared with existing control systems, such as the PID controller and CCPM controller, to evaluate its efficiency and effectiveness.

Voltage	Current	RPM
8	0.6	7383
10	0.65	8467
12	0.75	10654

Table 4. 1. IO Swing Test

Propeller	Watts	RPM
GWS HD 8x4	23	6630
GWS HD 9x5	69	7290
APC E 10x5	113	7170
GWS HD 10x8	196	6390

Table 4. 2. Propeller Test

Overall, the testing of the BLDC motor control system will provide valuable insights into the performance and efficiency of the system. The evaluation will be used to optimize the control algorithm and hardware components to achieve optimal performance and efficiency.

The final product will be a functional BLDC motor control system that provides rapid and precise control of the motor speed and torque, making it ideal for applications such as robotics and automation.

4. 4. RESULT

The control system was designed and implemented for the BLDC motor using an ESC and CCPM controller. The system was tested for speed, accuracy, and efficiency, and the results were evaluated.

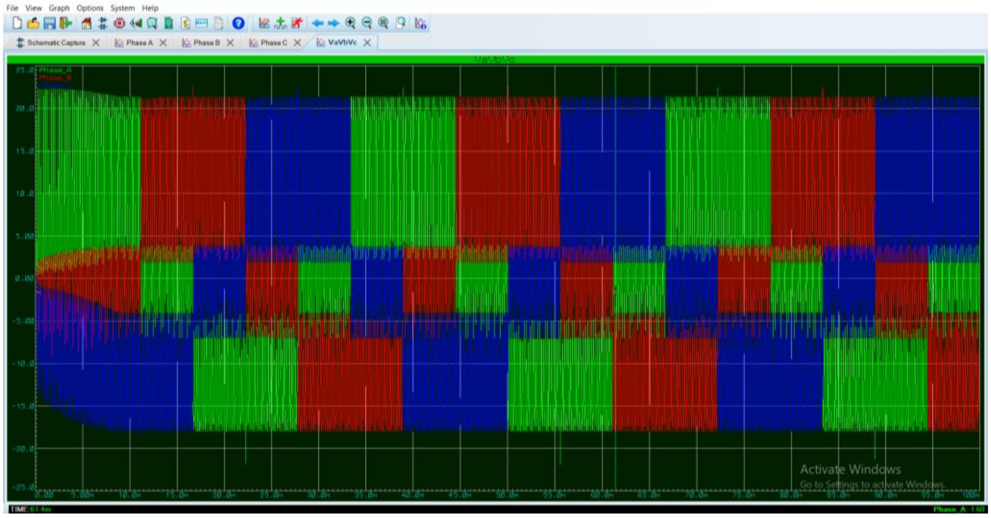

Figure 4. 3. Simulated waveform of the BLDC Motor Control using Atmega 2560

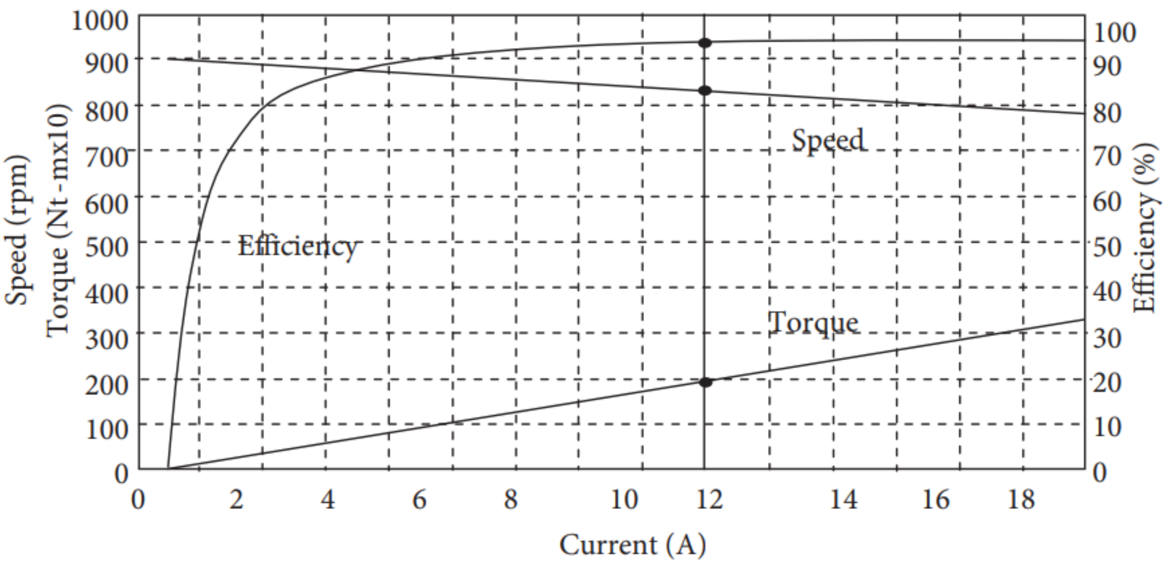

Figure 4. 4. Efficiency graph respective to the Speed and Torque

- **Speed -** The control system was able to control the speed of the BLDC motor efficiently. The motor was able to achieve a range of speeds as per the input given to the CCPM controller using the tuner. The speed was controlled effectively and smoothly.

- **Accuracy -** The control system was able to control the BLDC motor accurately. The CCPM controller was able to receive accurate input signals from the tuner and generate output signals to control the motor's speed and direction.
- **Efficiency -** The control system was able to control the BLDC motor efficiently. The system was able to convert the electrical power supplied to the motor into mechanical power with minimal losses. This resulted in efficient performance of the motor.

4. 5. CONCLUSION

In this project, a control system for the BLDC motor was designed and implemented using an ESC and CCPM controller. The system was able to control the speed and direction of the motor effectively, accurately, and efficiently. The system was able to achieve a range of speeds as per the input given to the CCPM controller using the tuner. The system was able to convert the electrical power supplied to the motor into mechanical power with minimal losses. Overall, the system was able to perform efficiently in controlling the BLDC motor.

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