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Design of BLDC Motor Controller For an Impact Wrench

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by

Munkh-Erdene Natsagdorj

Study program: Mechatronic Engineering

Student ID: B2100367

Supervisor 1/Examiner 1: Prof. Odbileg NorovRinchen

Supervisor 2/Examiner 2: Prof. YoungSuk Kim

Ulaanbaatar/Nalaikh

2025

Statutory Declaration

Munkh-Erdene Natsagdorj

B2100367

First Name, Last Name

Student ID Number


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ABSTRACT

This thesis focuses on the design of a Brushless DC (BLDC) motor controller for use in an impact wrench. The main objective of this project is to create a working motor controller design independently, using basic electronic components and commonly available tools. Rather than aiming for high efficiency or advanced performance, the emphasis is placed on understanding the fundamental design process and building a functional prototype by hand.

The system is built around the Arduino Uno microcontroller, which generates the required PWM signals for motor commutation. The IR2101 half-bridge gate driver is used to control the P75NF75 N-channel MOSFETs, which serve as the power switches for the three motor phases. The circuit also includes necessary passive components such as resistors and capacitors to support signal conditioning and circuit stability.

The control strategy is sensorless, relying on the back electromotive force (back-EMF) generated by the motor to detect rotor position. The entire design process, including schematic development and component selection, was carried out manually to ensure a thorough understanding of the system architecture.

This project demonstrates the basic steps involved in designing a simple BLDC motor controller, and serves as a learning experience in embedded systems, motor control, and circuit design.

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LIST OF ABBREVIATIONS

BLDC- Brushless DC Motor

RPM- Revolutions per Minute

IMP- Impact per Minute

EMF- ElectroMotive Force

UAVs- Unmanned Aerial Vehicles

FOC- Field-Oriented Control

DSPs- Digital Signal Processors

PWM- Pulse Width Modulation

UVLO- Under Voltage LockOut

MOSFET- Metal Oxide Semiconductor Field Effect Transistor.

Nm- Newton-meters

Ft- Foot-pounds

SRAM- Static Random-access Memory

EEPROM- Electrically Erasable Programmable Read-Only Memory.

UART- Universal Asynchronous Receiver / Transmitter

I2C- Inter-Integrated Circuit

SPI- Serial Peripheral Interface

1. INTRODUCTION

1.1 Background

Electric motors play a critical role in modern technologies. They are found in almost every sector from household appliances and vehicles to industrial machinery and smart devices. In particular, Brushless DC (BLDC) motors are becoming more sought due to their high efficiency, compact size, and long lifespan. Unlike brushed motors, BLDC motors don't rely on physical brushes for commutation, which reduces wear and maintenance while improving performance.

One of the common areas where BLDC motors are widely used is in power tools, such as impact wrenches, drills, and screwdrivers. These tools require reliable torque, precise speed control, and durability all of which BLDC motors can provide. However, these motors cannot function on their own; they need a proper motor controller to manage the switching of their phases and regulate speed and direction.

As a Mechatronic Engineering student, learning and understanding how to control motors is a fundamental part of the engineering field. Motors are at the heart of many mechatronic systems, and being able to design and control them opens the door to understanding how machines and equipment really work. My first supervisor emphasized that gaining hands-on experience in designing a motor controller, even a basic one, is extremely valuable and useful. It allows me to apply what I've learned in electronics, electrical field, control systems, and programming in a practical way.

With the growing use of BLDC motors in various industries, especially in portable and high-performance tools, understanding how these motors function and how they are controlled has become increasingly important. For students in engineering fields like mechatronics, working with motor control systems provides valuable hands-on experience that bridges theory with practical application. Designing and building such systems helps develop a deeper technical foundation, which is essential for solving real-world engineering problems in the future.

1.2 Aim and Objectives

The main objective of this thesis is to design a basic BLDC motor controller suitable for an impact wrench application. The goal is to carry out the entire design process independently in order to gain practical experience in motor control, microcontroller application, and circuit design. The project emphasizes learning through hands-on development rather than focusing on industrial-grade performance.

To achieve this, the following objectives were set:

- To understand the working principle of BLDC motors and their typical applications, especially in tools that require high torque and variable speed.
- To explore motor control methods and how to estimate rotor position with and without the need for physical sensors.
- To design a three-phase motor driver circuit that can provide the required switching signals and handle power delivery to the motor phases.
- To develop a control algorithm capable of generating the proper timing signals for motor commutation, using a microcontroller-based system.
- To verify the performance of the circuit and control algorithm using appropriate software tools.
- To document the full process of design, coding, and testing, as a way to build a strong foundation in motor control systems and related engineering skills.

2. LITERATURE REVIEW

2.1 Impact Wrench Fundamentals

2.1.1 Working principle

An electric impact wrench typically consists of a motor, a planetary gear set, a main pressure spring, and a shock mechanism. This design utilizes a planetary gear reduction system as the primary transmission method, allowing the tool to maintain a compact size, reduced weight, simple construction, high torque output, and straightforward control for an IPM (Internal Permanent Magnet) BLDC motor. The motor's rotational force is first transferred through the planetary gearbox to the main shaft. From there, the force is relayed through a ball mechanism, compressed by the main spring, to rotate the shock block. The shock block features two protruding claws that repeatedly strike the impact rod. This rod then delivers impact forces to the bolt or nut via the sleeve.

When the resistance torque at the bolt exceeds the torque delivered by the spring to the impact head, the impact head retracts along the V-groove of the shaft, constrained by the ball. This retraction causes the shock block and impact rod to disengage momentarily. However, driven continuously by the motor, the shock block rotates further, allowing the pawl to move past the shoulder and store additional rotational energy. Once realigned, the spring force drives the pawl back against the shoulder, generating a strong impact torque. This torque is transmitted through the sleeve to the bolt or nut, causing it to rotate incrementally. This impact cycle repeats until the bolt is fully tightened or loosened.

Compared to traditional manual tools, the repeated striking motion of the impact wrench significantly reduces user fatigue and shortens the time required for fastening operations. The combination of mechanical simplicity and high power output makes the electric impact wrench an essential tool across automotive, construction, and industrial applications.



Figure 1. Internal Structure of The Impact Wrench

2.1.2 Key Specifications

When selecting or designing an electric impact wrench, several technical specifications are important for assessing its performance and application range. It includes:

- **Torque Output**
Torque is the most important parameter of an impact wrench, defining its ability to tighten or loosen bolts and nuts under high load conditions. It is typically measured in Newton-meters (Nm) or foot-pounds (ft-lb). Higher torque values allow the tool to deal with larger fasteners and tougher materials. In practical applications, sufficient torque ensures that bolts are properly fastened without the need for additional manual effort, which is helpful in heavy machinery fields.
- **Speed (RPM)**
The rotational speed, expressed in revolutions per minute (RPM), indicates how fast the tool can spin under no-load conditions. While high RPM allows for faster operation and reduces task completion time, it must be properly matched with torque output. If speed is too high relative to torque, the tool may fail to loosen or tighten bolts effectively. Therefore, a balance between speed and torque is essential to maintain both efficiency and performance.

- **Impacts Per Minute (IPM)**

Impacts per minute (IPM) describe how many times the internal hammer mechanism strikes the anvil within one minute. A higher IPM value contributes to quicker energy delivery to the fastener, especially in tough or rusted connections. Frequent impacts are necessary in scenarios where continuous rotational force alone is insufficient to break the static friction of tight bolts.

- **Drive Size**

Drive size refers to the dimension of the square drive that holds sockets, and it is typically available in sizes like 1/4", 3/8", 1/2", 3/4", and 1". Larger drive sizes are associated with higher torque capacities, making them more suitable for industrial and heavy-duty applications. For example, a 1/2" drive is standard for automotive repairs, while 3/4" and 1" drives are commonly used in construction and large-scale machinery maintenance.

- **Motor Type**

The motor used in an electric impact wrench greatly affects its overall efficiency, durability, and performance. Many modern designs utilize brushless DC (BLDC) motors, which provide higher efficiency, lower heat generation, and reduced maintenance requirements compared to brushed motors. The absence of brushes minimizes mechanical wear, resulting in longer motor lifespan and more consistent torque delivery, which is especially important for professional and industrial users.

2.1.3 Main Types

1. Corded Electric Impact Wrench

Corded electric impact wrenches are powered directly from an alternating current (AC) source and are known for delivering consistent torque output without the limitations of battery life. These tools are commonly used in workshops, assembly lines, and construction sites where a stable power supply is readily available. Unlike cordless models, corded impact wrenches can operate continuously without the need for recharging or battery replacement, making them

suitable for high-volume or prolonged usage.

The core structure of a corded impact wrench typically includes a universal AC motor, a gear reduction system, and a hammer-and-anvil impact mechanism. When the trigger is activated, the motor drives the gears to rotate at high speed, and the impact mechanism periodically strikes the output shaft to produce strong torque pulses. This intermittent impact action allows the tool to loosen or tighten fasteners that would be difficult to handle with constant rotational force alone.

One major advantage of corded impact wrenches is their ability to deliver high and stable torque output over long periods without performance drops. They are often lighter than cordless models since they do not contain heavy battery packs. Additionally, corded wrenches can achieve higher peak power ratings because they are not limited by the battery voltage and current capacity.

2. Cordless Impact Wrench (Battery-Powered)

Cordless electric impact wrenches are widely used tools that offer portability, high torque output, and user convenience by operating on rechargeable lithium-ion batteries. They typically incorporate a brushless DC (BLDC) motor to drive a planetary gear reduction mechanism and an internal impact system. In modern cordless designs, the motor output is first reduced through a planetary gear system, and then transmitted to an impact mechanism consisting of components such as a shock block, balls, and springs. This structure converts the motor's continuous rotational motion into repetitive, high-intensity impact forces, allowing bolts and nuts to be tightened or loosened even under high resistance.

The performance of the cordless impact wrench strongly on the characteristics of its BLDC motor and, even more, on the design and functionality of its motor controller. The motor controller acts as the central element that governs the operation of the BLDC motor, ensuring that it responds accurately and efficiently to various user inputs and working conditions. It is responsible for interpreting the trigger position to control motor speed, adjusting torque output based on real-time load conditions, and monitoring rotational feedback to ensure smooth and stable operation. Advanced motor controllers also incorporate protection features such as overcurrent protection, thermal monitoring, and stall detection, which help to enhance the durability and reliability of both the motor and the entire tool. Furthermore, the controller must manage the commutation process of the BLDC motor, especially in sensorless designs, by

estimating rotor position and timing the switching of current precisely to maintain efficient torque generation. This precise electronic control is essential not only for achieving optimal performance but also for improving battery life, minimizing energy losses, and ensuring consistent impact force delivery during operation. In the context of impact wrenches, where the load can vary rapidly due to the sudden application and release of torque, a well-designed motor controller becomes even more important to ensure fast response, strong impact performance, and stable user experience under varying working conditions.



Figure 2. Cordless Impact Wrench [1]

3. Pneumatic (Air) Impact Wrench

Pneumatic, or air-powered, impact wrenches are one of the most common and traditional types of impact tools used in automotive, industrial, and maintenance applications. They operate using compressed air as the power source, which drives an internal motor and impact mechanism to deliver high torque outputs efficiently and reliably.

The structure of an air impact wrench typically consists of an air motor, a gear reduction system, and a hammer-and-anvil type impact mechanism. When compressed air enters the motor, it causes the rotor to spin, which in turn drives the hammer mechanism. The hammer periodically strikes the anvil connected to the output shaft, producing strong, sudden bursts of torque. This repeated impacting allows the tool to loosen or tighten bolts and nuts that require much higher torque than can be achieved with continuous rotation alone.

Their high power-to-weight ratio is the main benefit compared to other types. Since they do not

carry onboard motors or batteries, air wrenches are usually lighter and more compact compared to electric models with similar torque ratings. They are also less prone to overheating during continuous heavy use, making them highly suitable for demanding environments such as automotive repair shops, assembly lines, and construction sites.

However, pneumatic impact wrenches require a continuous supply of compressed air, typically provided by a separate air compressor. This setup limits their portability and can increase system complexity, as users must manage air hoses and compressors. The performance of the tool also heavily depends on maintaining sufficient air pressure and flow, which means that any drop in compressor performance can directly affect the torque output of the wrench.

4. Hydraulic Impact Wrenches

Unlike electric or pneumatic models, hydraulic impact wrenches use pressurized hydraulic fluid to generate rotational motion and impact force. These tools are often used in heavy industries such as shipbuilding, mining, oil and gas operations, and large-scale construction projects.

The working principle of a hydraulic impact wrench involves a hydraulic motor, which is driven by fluid pressure supplied by an external hydraulic pump. As the pressurized fluid enters the motor, it causes a rotor to spin, which then drives a mechanical impact system, usually a hammer and anvil configuration. The hydraulic system provides smooth, steady energy delivery, allowing for high torque output while minimizing vibration and tool wear.

One of the key advantages of hydraulic impact wrenches is their ability to produce extremely high torque values while maintaining a compact and durable design. Because hydraulic fluid is incompressible, hydraulic systems can deliver more consistent and powerful force compared to pneumatic systems, where air compressibility can cause energy losses. This makes hydraulic wrenches ideal for tasks where bolt preloading, precise torque application, and repeatability are critical.

Additionally, hydraulic impact wrenches are highly resistant to environmental factors such as moisture, dust, and extreme temperatures, which often makes them preferable in outdoor and harsh working environments. Some hydraulic impact wrenches are even designed for underwater operations, where electric and pneumatic models cannot function reliably. However, the use of hydraulic wrenches introduces certain limitations. They require a hydraulic power pack and hoses, which increases system complexity and reduces portability. The setup can be

bulky and may not be practical for everyday workshop use compared to lighter cordless electric tools. Moreover, the cost of hydraulic systems is generally higher, both in terms of initial investment and maintenance.

2.2 Overview of BLDC Motor

2.2.1 Working Principle and Structure

BLDC (Brushless DC) motors are classified as a type of synchronous motor. In a synchronous motor, the magnetic field generated by the stator and the magnetic field produced by the rotor rotate at the same frequency, maintaining a constant alignment during operation. Unlike conventional induction motors, BLDC motors operate without "slip," meaning the rotor rotates exactly in sync with the stator's magnetic field. The absence of slip leads to improved efficiency and more precise control of speed and torque. BLDC motors are manufactured in different configurations, including single-phase, two-phase, and three-phase designs. In each case, the stator is wound accordingly to match the number of phases. Among these, three-phase BLDC motors are by far the most common and widely utilized due to their superior efficiency, smoother torque production. Their popularity is also driven by the fact that three-phase configurations allow for simpler control algorithms and more balanced operation compared to single-phase or two-phase designs.

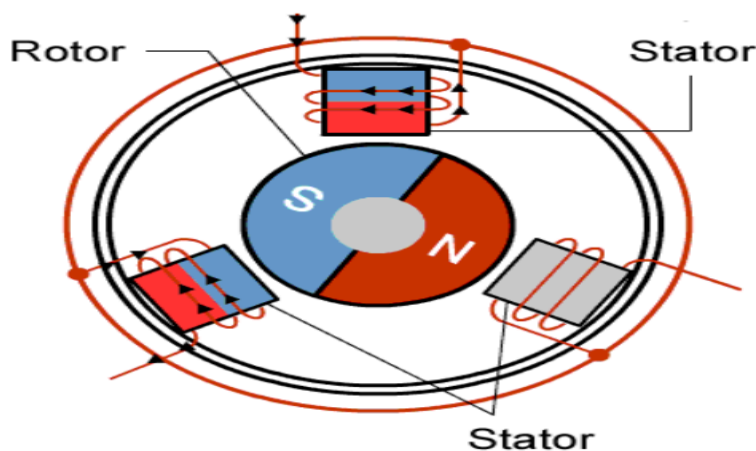


Figure 3. BLDC Motor [2]

Stator

The stator of a BLDC motor is typically constructed from thin laminated sheets of steel stacked together to minimize eddy current losses. Windings are positioned in axially-cut slots along the inner surface of the stator. Although the stator structure is similar to that found in traditional induction motors, the winding distribution is different to meet the specific requirements of BLDC operation. Most commonly, BLDC motors use three stator windings connected in a star (Y) configuration. Each winding is formed by several interconnected coils placed strategically within the slots around the stator's inner periphery, creating an even number of magnetic poles. Based on how the coils are connected and the type of generated back electromotive force (back-EMF).

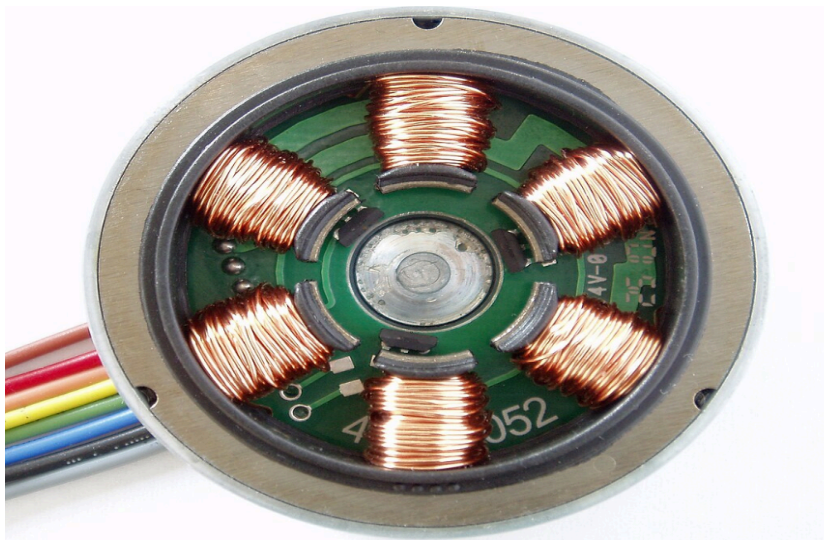


Figure 4. Stator of 3 Phase BLDC Motor [3]

There are two main variants of stator windings: trapezoidal and sinusoidal. Trapezoidal BLDC motors produce a back-EMF waveform that is trapezoidal, while sinusoidal BLDC motors generate a sinusoidal back-EMF, as shown in Figures 1 and 2. This also affects the shape of the phase current, which mirrors the back-EMF waveform. As a result, sinusoidal motors generally offer smoother torque output compared to trapezoidal motors. However, achieving a sinusoidal back-EMF requires a more complex winding layout, leading to increased copper usage and higher manufacturing costs.

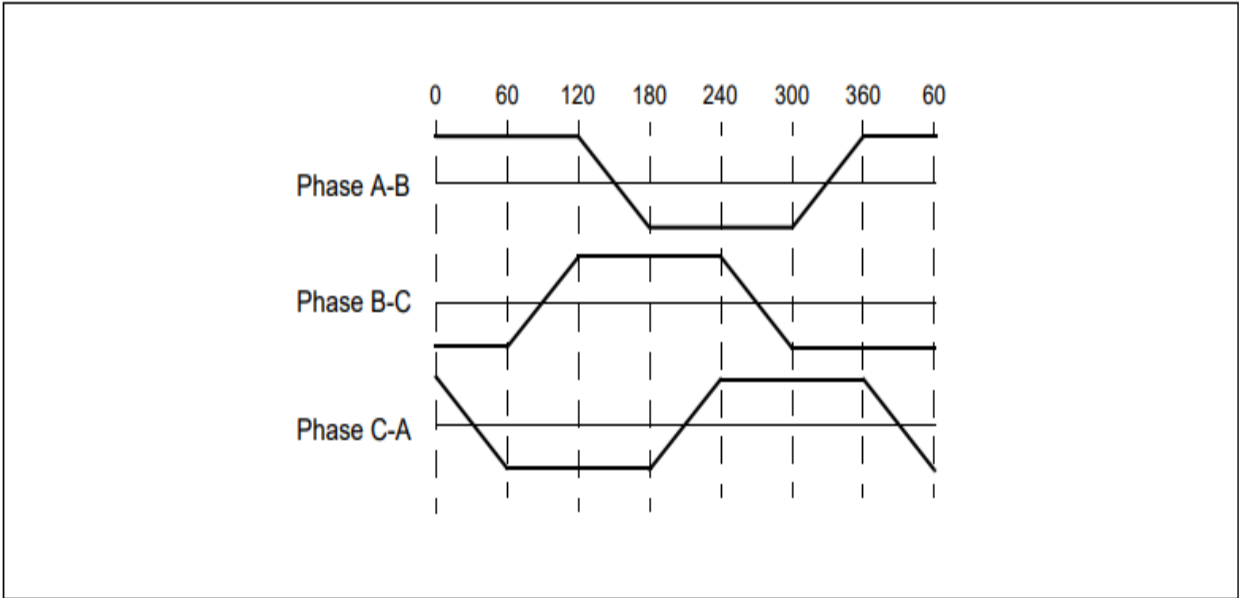


Figure 5. Trapezoidal Back EMF [4]

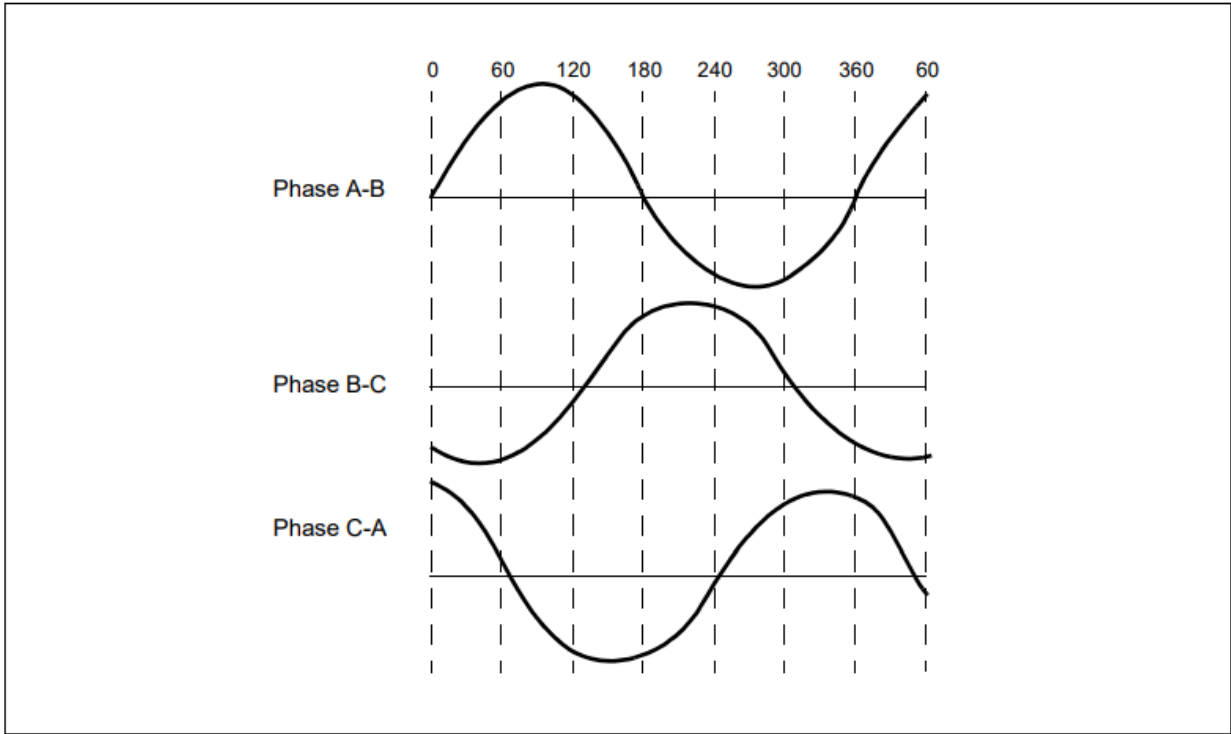


Figure 6. Sinusoidal Back EMF [4]

The selection of a motor is also influenced by its voltage rating, which must match the capability of the control power supply. Motors rated at 48 volts or lower are typically found in automotive applications, robotics, and small-scale motion control, while motors rated at 100 volts or more are commonly used in appliances, industrial automation, and larger-scale equipment.

Rotor

The rotor in a BLDC motor is composed of permanent magnets that are arranged in alternating North (N) and South (S) poles. Typically, the rotor can have between two to eight pole pairs depending on the design specifications and torque requirements of the motor. The selection of the magnetic material used for the rotor is critical, as it directly influences the motor's magnetic field strength, size, efficiency, and overall performance. In earlier designs, ferrite magnets were commonly utilized due to their wide availability and low manufacturing cost. However, ferrite magnets are limited by their relatively low magnetic flux density, which means that for a given torque output, the motor tends to be larger and heavier.

With advancements in material science, rare-earth magnets have become the preferred choice for high-performance applications. Materials such as Neodymium (Nd), Samarium Cobalt (SmCo), and Neodymium-Iron-Boron (NdFeB) alloys offer significantly higher magnetic flux density compared to ferrite magnets. This enables motor designers to create more compact and lightweight rotors while achieving the same or greater torque output. Rare-earth magnets also contribute to improved thermal stability and energy efficiency, which is particularly beneficial in high-demand applications such as cordless impact wrenches and industrial machinery.

Although rare-earth magnets are more expensive, their advantages in terms of size reduction, weight savings, and torque enhancement often outweigh the additional cost, especially in applications where space and performance are critical factors. Research and development efforts continue to focus on improving magnetic materials to achieve even higher flux densities and better resistance to demagnetization, ensuring that future BLDC motors will become even more compact, powerful, and reliable.

Hall sensors

In contrast to brushed DC motors, BLDC motors use electronic commutation instead of mechanical brushes. To make the motor rotate, the stator windings need to be energized in a specific sequence. Knowing the exact position of the rotor is essential to determine which winding should be energized next. In most BLDC motors, this rotor position is detected using Hall effect sensors that are installed inside the stator. Typically, there are three Hall sensors placed at the non-driving side of the motor. As the rotor spins, its magnetic poles pass close to these sensors, causing them to output either a high or low signal depending on whether a north or south pole is nearby. By reading the combination of signals from the three Hall sensors, the motor controller can figure out the correct commutation sequence needed to keep the motor running smoothly.

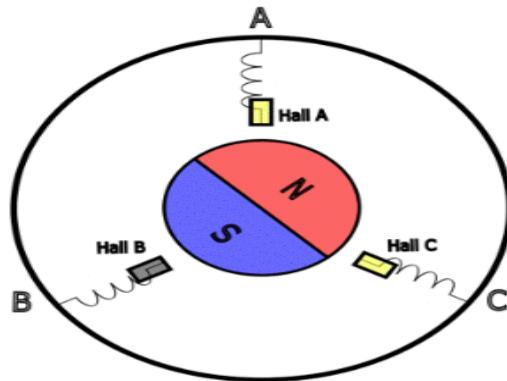


Figure 7. Typical Hall Sensors on Rotor

2.2.2 Comparison to other motor types

To better understand the advantages and limitations of brushless DC (BLDC) motors, it is helpful to compare them with other common motor types. Table 1 provides a comparison between BLDC motors and brushed DC motors, focusing on differences in commutation method, efficiency, maintenance requirements, and application suitability. Similarly, Table 2 presents a comparison between BLDC motors and induction motors, highlighting key distinctions such as control complexity, efficiency, torque characteristics, and typical areas of use. These comparisons clearly demonstrate the superior performance and reliability of BLDC motors in applications requiring high efficiency, compact size, and precise control.

Table 1. Comparing BLDC motor to brushed dc motor

Aspect	BLDC motor	Brushed DC Motor
Commutation	Electronic (using controller)	Mechanical (using brushes and commutator)
Maintenance	Low (no brushes to wear out)	High (brushes and commutator wear out)
Efficiency	High (less friction, better energy use)	Lower (friction losses from brushes)
Lifespan	Long	Shorter (due to brush wear)
Control complexity	High (requires electronic controller)	Simple (direct voltage control possible)
Noise	Low	High (Sparking from brushes)
Cost	Higher (due to controller and magnets)	Lower (simple structure)
Torque to weight ratio	High	Moderate
Speed range	Wide (good for high-speed applications)	Limited (brush wear at high speeds)
Applications	Power tools, drones, EVs, industrial automation	Toys, basic motors, simple low-cost devices

Table 2. Comparing BLDC motor to induction motor

Aspect	BLDC motor	Induction Motor
Commutation	Electronic (controlled by external controller)	Electromagnetic induction (no electronic commutation)
Rotor Type	Permanent magnets	Squirrel-cage or wound rotor
Efficiency	High (due to no slip and permanent magnets)	Moderate to high (depends on load and design)
Maintenance	Low (no brushes, fewer wear parts)	Low (very robust, no brushes)
Torque at Low Speed	High (good for variable-speed applications)	Moderate (requires VFD for good low-speed performance)
Control Complexity	High (needs sophisticated controllers)	Moderate (basic operation is simple, but precise control needs VFD)
Slip	None (rotor and magnetic field rotate synchronously)	Exists (rotor lags behind magnetic field)
Size and Weight	More compact for the same torque	Larger for the same torque output
Cost	Higher (expensive magnets and controllers)	Lower (especially in mass production)
Applications	Drones, cordless tools, electric vehicles, precision drives	Pumps, fans, industrial machines, HVAC systems

2.2.3 Applications

- Electric Vehicles

These BLDC motors are essential components in modern electric vehicles, including electric cars, scooters, and bicycles. Their ability to deliver high torque and excellent efficiency makes them ideal for providing the strong and smooth propulsion required in

these applications. Because of their high power density and energy efficiency, they significantly contribute to extending the battery life and increasing the overall range of the vehicle. Moreover, the precise control and compact size of BLDC motors allow for better vehicle performance, smoother acceleration, and reduced energy consumption, making them highly suitable for the evolving electric mobility sector.

- Drones and Unmanned Aerial Vehicles (UAVs)

Drones and UAVs heavily rely on BLDC motors to achieve stable, responsive, and energy-efficient flight. These motors provide the necessary torque and high-speed operation needed to control the propellers effectively. Their lightweight structure and high efficiency help to reduce the overall weight of the drone, resulting in longer flight times and better maneuverability. Additionally, the quick response and precise speed control offered by BLDC motors are critical for applications where stability and agility are important, such as aerial photography, surveying, and delivery services.

- Industrial Automation

In the field of industrial automation, BLDC motors are widely used in robots, CNC machines, conveyor systems, and other automated equipment. Their ability to provide precise speed and position control with high reliability and low maintenance requirements makes them ideal for industries that demand continuous and accurate operations. The absence of brushes also leads to reduced downtime and longer service life, making BLDC motors an economical and efficient choice for modern manufacturing and automation processes.

- Home Appliances

BLDC motors are becoming popular in various home appliances, including washing machines, refrigerators, vacuum cleaners, and air conditioners. Their high energy efficiency helps to lower electricity consumption, while their quiet operation enhances user comfort. Furthermore, the durability and reduced maintenance of BLDC motors make them suitable for devices that are used frequently in daily life, contributing to the overall reliability and convenience of modern home appliances.

- HVAC Systems

In HVAC (Heating, Ventilation, and Air Conditioning) systems, BLDC motors are typically used to drive fans and blowers. Their variable speed capabilities enable better temperature regulation, improved airflow control, and higher system efficiency. By adjusting motor speed according to demand, HVAC systems powered by BLDC motors can operate more quietly, consume less energy, and provide a more comfortable environment, making them an excellent choice for both residential and commercial buildings.

- Medical Devices

Medical equipment demands high levels of precision, reliability, and quiet operation, all of which BLDC motors are well-suited to deliver. Applications such as ventilators, CPAP machines, infusion pumps, and robotic surgical instruments use BLDC motors to achieve smooth, accurate control with minimal noise. The reliability and long service life of these motors are crucial in medical settings where equipment failure is not acceptable and continuous operation is often necessary to support patient care.

- Power Tools

Cordless power tools such as drills, screwdrivers, impact wrenches, and grinders benefit greatly from the use of BLDC motors. Their high power-to-weight ratio allows for compact, lightweight designs without sacrificing performance. Additionally, the efficiency of BLDC motors leads to longer battery life, enabling users to work for extended periods without frequent recharging. Their robustness and consistent torque output also make them ideal for heavy-duty and professional applications.

- Renewable Energy Systems

BLDC motors are also being used in renewable energy applications, such as in small wind turbines and solar tracking systems. Their high efficiency and ability to provide reliable operation under varying load conditions make them well-suited for maximizing energy conversion. In solar tracking systems, for example, BLDC motors help adjust the position of solar panels to follow the sun's movement, thereby improving overall energy collection and system efficiency. Their durability and low maintenance also make them attractive choices for remote or off-grid installations.

2.3 Review of Existing Control Methods

- Six-Step Commutation (Trapezoidal Control)

Trapezoidal commutation is one of the most traditional and widely used methods for controlling BLDC motors. In this approach, two of the three motor phases are energized at any given time, while the third phase remains unpowered. The energization sequence follows six distinct steps to complete one full electrical cycle, which is why it is called "six-step" commutation. Each step corresponds to a specific combination of active phases, producing a rotating magnetic field that drives the rotor.

The method is named "trapezoidal" because the back electromotive force (back-EMF) generated by the motor follows a trapezoidal waveform. To achieve efficient commutation, the current supplied to the motor phases is ideally synchronized with the flat portions of the back-EMF waveform. As a result, the motor can produce almost constant torque, although some torque ripple is still present compared to sinusoidal methods.

Trapezoidal control is relatively simple to implement both in hardware and software. It typically uses rotor position feedback, obtained either from Hall effect sensors or through sensorless techniques such as back-EMF zero-crossing detection. Because of its straightforward structure and low computational requirements, six-step commutation is well-suited for applications where simplicity, cost-effectiveness, and robustness are more important than extremely smooth torque production. Examples include electric drills, impact wrenches, fans, and pumps.

However, the major drawback of trapezoidal commutation is the presence of torque ripple, especially at low speeds, which can lead to noise and vibration. Despite this, the method remains a popular choice for many practical applications where the advantages outweigh the minor disadvantages.

- Sinusoidal Commutation Method

Sinusoidal commutation is a more advanced control method for BLDC motors compared to trapezoidal (six-step) commutation. In this technique, the motor phases are energized using sinusoidal current waveforms instead of rectangular pulses. The goal is to make the stator magnetic field rotate smoothly, resulting in a more continuous and uniform torque production with minimal ripple.

In sinusoidal commutation, the current supplied to each motor phase is carefully controlled to follow a sinusoidal pattern that is synchronized with the rotor position. Accurate knowledge of the rotor angle is essential, typically achieved by using precise position sensors such as encoders or high-resolution Hall sensors. In some cases, sensorless methods using back-EMF or observer-based algorithms can also be applied for sinusoidal control.

One of the main advantages of sinusoidal commutation is the reduction of torque ripple and mechanical vibration. By ensuring that the phase currents vary smoothly over time, the motor generates a constant electromagnetic torque, which significantly improves efficiency, quietness, and overall performance. This makes sinusoidal commutation especially suitable for applications where smooth motion and low noise are critical, such as robotics, high-end home appliances, and medical devices.

On the contrary, sinusoidal commutation requires more complex hardware and software compared to trapezoidal control. It demands continuous rotor position tracking and real-time adjustment of current waveforms, leading to greater computational load on the controller. Despite the increased complexity, the benefits in terms of smoother operation and better energy efficiency often justify the use of sinusoidal control in precision-driven applications.

Overall, sinusoidal commutation provides a higher-performance alternative to six-step control, at the cost of greater design complexity and system requirements.

Trapezoidal Commutation



Sinusoidal Commutation



Figure 8. Waveform of Trapezoidal And Sinusoidal Commutation [5]

- Field-Oriented Control (FOC) Method

Field-Oriented Control (FOC) is a highly precise technique used for controlling BLDC and PMSM (Permanent Magnet Synchronous Motor) motors. Unlike trapezoidal or sinusoidal commutation, FOC aims to control the motor's magnetic field in a way that decouples the torque and flux components, allowing them to be managed independently. This enables smoother operation, higher efficiency, and precise dynamic response even under varying load conditions.

In FOC, the three-phase motor currents are mathematically transformed into two orthogonal components: the direct-axis (d-axis) current and the quadrature-axis (q-axis) current, using a mathematical operation known as the Clarke-Park transformation. The d-axis current controls the flux (magnetic field strength), while the q-axis current controls the torque. By controlling these two components separately, it becomes possible to achieve optimal motor performance under all operating conditions.

The rotor position information is critical for FOC to properly align the stator current vector with the rotor magnetic field. This position is usually obtained using high-precision sensors like encoders or resolvers. However, sensorless FOC techniques have also been developed, using estimators and observers to calculate rotor position from the motor's terminal measurements.

Field-Oriented Control (FOC) is known for delivering several important advantages when applied to BLDC motors. One of its primary benefits is the significant reduction of torque ripple, which results in exceptionally smooth and quiet motor operation. FOC also provides improved dynamic response, allowing the motor to adjust torque and speed rapidly based on load conditions. Another important advantage is its ability to optimize the torque produced per unit of current, thereby enhancing the overall energy efficiency of the motor.

Despite these benefits, Field-Oriented Control comes with notable challenges. The method demands advanced hardware, such as high-performance microcontrollers or digital signal processors (DSPs), capable of handling complex calculations in real-time. It also requires detailed motor modeling and precise rotor position feedback to function correctly. Due to its complexity and higher implementation cost, FOC is most commonly used in high-end applications where superior motor performance is critical, including electric vehicles, sophisticated industrial machinery, robotics, and aerospace technologies.

In summary, although Field-Oriented Control offers unmatched performance and efficiency in motor control, it also introduces significant system complexity, making it suitable primarily for demanding and precision-focused applications.

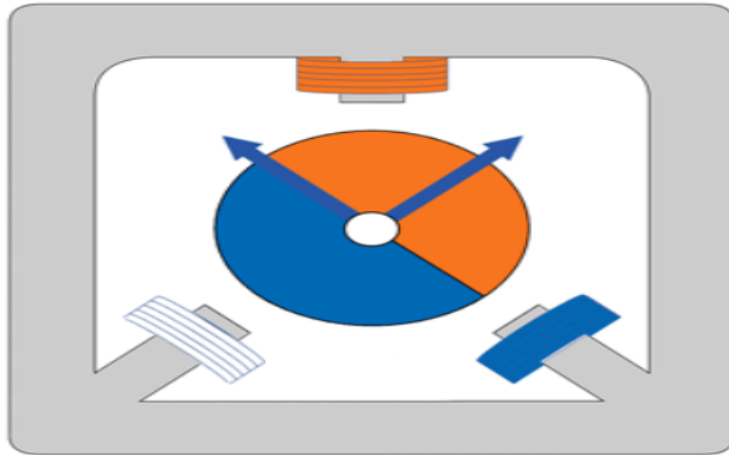


Figure 9. Field Oriented (Vector) Control [5]

3. METHODOLOGY

3.1 Microcontroller Selection

In the design of the BLDC motor controller for my thesis project, I selected the Arduino Uno as the microcontroller unit. Several factors influenced this choice. Firstly, the Arduino Uno is based on the ATmega328P microcontroller, which offers sufficient processing speed, memory capacity, and input/output capability needed for basic sensorless BLDC motor control. It provides a simple and flexible development environment, allowing for easy programming, debugging, and modification of control algorithms. Additionally, the wide community support and availability of libraries make Arduino Uno a practical option for rapid prototyping and experimental validation.

Considering the requirements of this project such as PWM generation, back-EMF signal processing, and real-time commutation control the Arduino Uno meets the necessary performance criteria without introducing unnecessary complexity or cost. Its sufficient number of digital and analog input/output pins allows integration with motor driver circuits, position feedback mechanisms, and system protection features. Furthermore, the Arduino Uno's

simplicity and compatibility with simulation tools made it an appropriate choice for developing and testing the BLDC motor controller within the scope of this thesis work.

In this project, the Arduino Uno serves as the central control unit responsible for managing the operation of the BLDC motor. Its primary role is to generate the appropriate Pulse Width Modulation (PWM) signals required for switching the MOSFETs in the motor driver circuit, based on the real-time rotor position feedback. Since this design uses a sensorless method, the Arduino Uno also processes the back-EMF signals from the motor terminals to estimate rotor position and determine the correct commutation sequence. It acts as the main interface between the user inputs (such as trigger control) and the motor's electrical outputs, ensuring smooth and efficient motor operation. The simplicity, sufficient computational capability, and flexibility of the Arduino Uno make it an ideal platform for implementing and testing the BLDC motor control algorithms developed during this thesis.

Table 3. Arduino Uno Specifications

Specifications	Details
Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	7-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P) (0.5 KB used by bootloader)
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz
Communication Interfaces	UART, I2C, SPI

3.2 Selection of Gate Driver

For the motor drive stage of the BLDC motor controller, the IR2101 half-bridge gate driver IC was selected. The IR2101 is a high-voltage, high-speed power MOSFET and IGBT driver with independent high-side and low-side referenced output channels. It is capable of driving both the high-side and low-side MOSFETs required for BLDC motor commutation. The IR2101 features a floating high-side driver which can operate up to 600 V, making it suitable for handling the voltage levels typical in motor control applications. It also includes built-in under-voltage lockout (UVLO) protection for both the high and low sides, ensuring reliable operation even under varying supply conditions.

The use of the IR2101 simplifies the design of the motor controller by reducing the complexity of the gate drive circuitry, while still providing fast switching speeds and strong noise immunity, both of which are crucial for efficient and robust motor operation. Additionally, the logic-level input compatibility of the IR2101 matches well with the 5V output levels of the Arduino Uno, allowing direct interfacing without the need for additional level-shifting circuits.

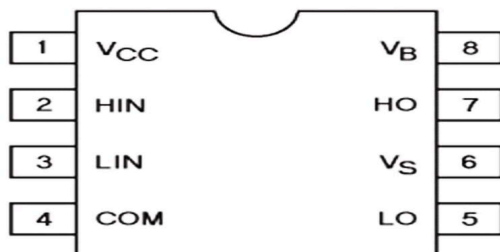


Figure 10. IR2101 Gate Driver

- **VCC (Pin 1):** This is the logic supply voltage input. It powers the internal control circuitry of the IR2101. Typically connected to a +5V or +12V regulated supply.
- **HIN (Pin 2):** This is the logic input that controls the state of the output pins (HO and LO). A high or low signal at this pin determines which MOSFET (high-side or low-side) is turned on.

- **LIN (Pin 3):** Logic input for controlling the low-side MOSFET. A high signal at this pin turns on the low-side MOSFET.
- **COM (Pin 4):** This is the common ground reference for the low-side driver and logic inputs. It should be connected to the source of the low-side MOSFET and the system ground.
- **LO (Pin 5):** This is the low-side driver output. It is connected to the gate of the low-side MOSFET and delivers the switching signal directly from the internal driver circuit.
- **VS (Pin 6):** This is the floating supply return for the high-side driver. It is typically connected to the source of the high-side MOSFET, which is also the output of the half-bridge.
- **HO (Pin 7):** This is the high-side driver output. It connects to the gate of the high-side MOSFET and provides the necessary voltage and current to turn the high-side switch on and off.
- **VB (Pin 8):** This is the floating high-side supply voltage input. It provides power to the high-side driver circuitry. VB is typically connected to a bootstrap capacitor that is charged from VCC.

In this project, the IR2101 plays a critical role by acting as the intermediate stage between the microcontroller and the power MOSFETs. It receives the PWM signals generated by the Arduino Uno and appropriately amplifies and conditions these signals to drive the MOSFET gates with sufficient voltage and current. By ensuring precise and synchronized switching of the MOSFETs, the IR2101 enables efficient commutation of the BLDC motor phases, directly affecting the motor's performance, efficiency, and reliability.

Table 4. IR2101 Specifications

Parameter	Value
High-side floating supply	Up to 600V
Gate drive voltage	10 – 20V
Output current (source)	120 mA typical
Output current (sink)	250 mA typical
Turn-on delay time	~160 ns
Turn-off delay time	~140 ns
Deadtime (typical)	~270 ns (depending on variant)
Logic input threshold	3V (typical) (TTL compatible)
Bootstrap operation	Supported

3.3 Power stage design

In this project, I am using P75NF75 N-channel MOSFETs, driven by the IR2101 gate driver ICs, and controlled through PWM signals generated by the Arduino Uno. The MOSFETs are configured in a three-phase inverter bridge (six-switch configuration), where each motor phase is connected between a high-side and low-side MOSFET.

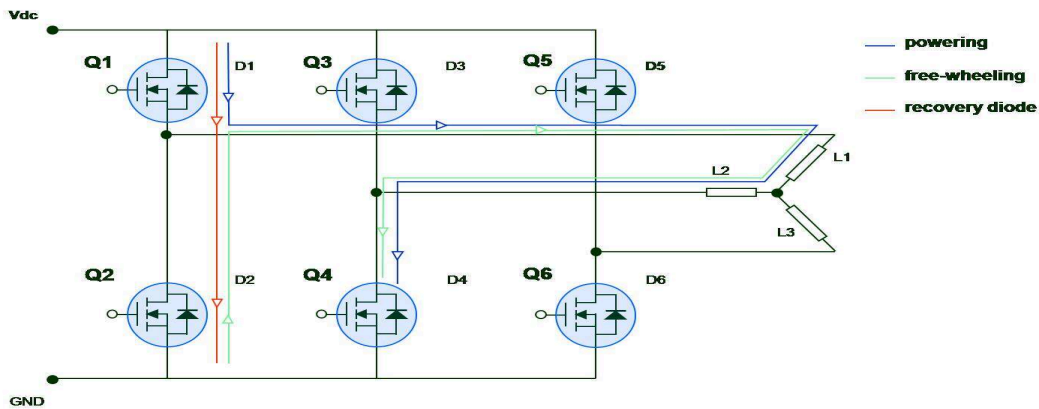


Figure 11. Three Phase Inverter Bridge [6]

The P75NF75 was selected due to its high current handling capability (up to 80A), low on-resistance ($R_{DS(on)} \approx 11 \text{ m}\Omega$), and good switching characteristics. These features ensure low conduction losses and efficient power delivery, which are essential for handling the rapid switching and high current spikes typical in BLDC motor operation.

The IR2101 gate driver amplifies the Arduino's PWM control signals to appropriate levels needed to fully switch the MOSFETs on and off. For high-side switching, bootstrap circuits are used, consisting of a bootstrap diode and capacitor connected to the IR2101 driver. This allows the high-side MOSFETs to operate correctly even as their source potential follows the motor phase voltage. The power stage must also manage the back EMF and transient currents produced by the motor. The intrinsic body diodes of the P75NF75 MOSFETs provide a path for these currents, protecting the circuit during freewheeling conditions.

Key Features of the P75NF75:

- Drain-Source Voltage (V_{DSS}): 75V
- Continuous Drain Current (I_D): 80A (at 25°C)
- $R_{DS(on)}$: 11 m Ω (at $V_{GS} = 10V$)
- Gate Threshold Voltage ($V_{GS(th)}$): 1-3V
- Power Dissipation (P_D): 150W
- Package Type: TO-220

3.4 Commutation logic

Throughout this thesis, sensorless commutation is implemented by detecting the Back Electromotive Force (Back EMF) of the motor. Back EMF is a voltage generated in the stator windings as the rotor turns within the magnetic field. The voltage induced in each of the stator windings is proportional to the rotor speed and provides critical information about the rotor's position without the need for physical position sensors like Hall effect sensors. The Arduino Uno

microcontroller plays a pivotal role in processing this Back EMF and controlling the commutation process.

Back EMF and Rotor Position Detection

As the rotor of the BLDC motor turns, the Back EMF generated in the stator windings can be used to infer the rotor's position. When the rotor moves, it induces a voltage in the stator coils that can be sensed as an AC voltage waveform. This Back EMF waveform provides information about the rotor's speed and position in real-time. By analyzing the zero-crossing points of the Back EMF, the Arduino Uno can estimate the rotor's position and determine when to change the commutation state.

Unlike the traditional method, which uses Hall effect sensors to detect rotor position, the sensorless technique avoids the need for physical sensors. This reduces the overall complexity and cost of the system, making it more efficient for certain applications.

Sequence of Commutation in Sensorless Control

In sensorless control, the commutation sequence is determined by detecting the Back EMF of the motor. The sequence follows these steps:

- **Back EMF Detection:** The Arduino Uno monitors the voltage induced in the stator windings (Back EMF) to determine the rotor's position. Since the motor is three-phase, the Arduino uses the Back EMF from two of the three stator windings to estimate the rotor's position.
- **Zero-Crossing Detection:** By detecting the zero-crossings (when the Back EMF waveform crosses the horizontal axis), the Arduino Uno can pinpoint the rotor's position. This is crucial because the zero-crossing points mark when the magnetic poles of the rotor align with the stator poles, signaling the optimal time to switch the current in the stator windings.
- **PWM Generation:** Once the rotor position is detected, the Arduino Uno generates the appropriate PWM signals to drive the MOSFETs. These signals switch the MOSFETs in the correct sequence to energize the stator windings. The generated PWM signals determine the voltage applied to the motor and control the motor's speed and torque.

- MOSFET Switching: The PWM signals are fed to the IR2101 gate driver, which controls the switching of the MOSFETs in the power stage. The correct commutation sequence ensures that the rotor continues to rotate smoothly and efficiently. The torque generated by the motor is proportional to the timing and sequence of the commutation.

3.5 Passive components

In the sensorless BLDC motor controller design, various passive components are integrated to support signal conditioning, gate driving and regulation of voltage and current. Their specific roles and configurations are as follows:

1. Resistors

- Three 33 k Ω and three 10 k Ω resistors are configured as voltage dividers. These are connected from each of the BLDC motor's three phases (A, B, and C) to ground. The divided voltage signals are fed into the analog input pins of the Arduino Uno. This allows the Arduino to monitor the back-EMF voltages from each phase, which is essential for sensorless commutation.
- Three 33 k Ω resistors are connected from each motor phase (A, B, C) to a common node to form a virtual neutral point. This virtual ground reference is used to determine the zero-crossing points of the back-EMF signals, enabling precise timing for phase commutation without physical sensors.
- Six 10 Ω resistors are used as gate resistors in the gate drive circuitry between the IR2101 MOSFET driver and the gates of the N-channel MOSFETs (P75NF75). These resistors help to:
 - Limit the inrush current to the MOSFET gate during switching
 - Improve overall switching performance and reduce EMI

2. Capacitors

- Three 2.2 μF ceramic capacitors are placed between the VB and VS pins of the IR2101 gate drivers. These capacitors form part of the bootstrap circuit, providing the required gate voltage for high-side MOSFET operation.
- Three 10 μF electrolytic capacitors are used for power supply decoupling and filtering to stabilize the 12 V supply used by the IR2101 drivers and other components.

3. Diodes

- Three 1N4148 fast switching diodes are included in the bootstrap circuits of the IR2101 drivers. These diodes:
 - Allow current to charge the bootstrap capacitor when the low-side MOSFET is on
 - Prevent reverse voltage from damaging the bootstrap path

4. Push Buttons

- Two push buttons are connected to the Arduino Uno for manual user control:
 - One for increasing motor speed
 - One for decreasing motor speed

5. Power Supply

- A regulated 12 V DC power supply is used to power the IR2101 gate drivers and the MOSFETs. The Arduino Uno is powered separately via USB or a regulated 5V source.

4. SYSTEM IMPLEMENTATION AND RESULT

4.1 System design

Here is the schematic of the sensorless BLDC motor controller designed using an Arduino Uno, IR2101 gate drivers, and N-channel MOSFETs. The Arduino generates control signals for the gate drivers, which in turn switch the MOSFETs to power the three-phase BLDC motor. A set of resistors is used to create voltage dividers for back-EMF sensing, allowing the Arduino to detect rotor position without Hall sensors. Additional resistors form a virtual neutral point to assist with zero-crossing detection. Push buttons are included for speed control, and capacitors and diodes are used for signal stability and proper driver operation.

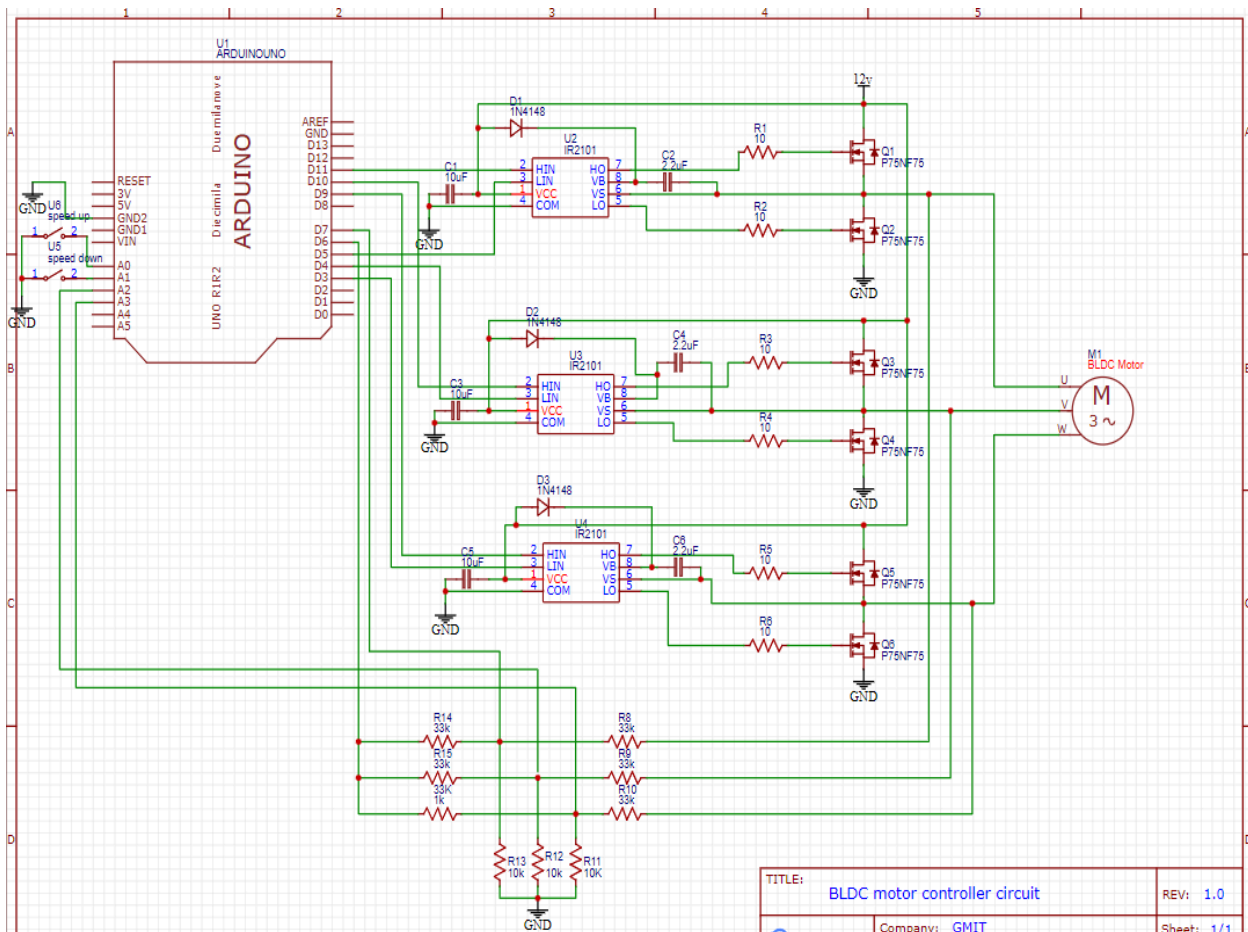


Figure 12. Design Circuit of Sensorless BLDC Motor Controller

4.2 Simulation setup

This simulation was illustrated to verify the PWM control signals that would be used to drive the BLDC motor controller. Since LTspice does not support direct simulation of microcontrollers such as the Arduino Uno, the PWM outputs were simulated using ideal voltage sources configured to produce square wave signals.

The simulation setup included:

- Six voltage sources representing the six PWM signals that would be generated by an Arduino Uno in a real circuit,
- Each signal was configured with appropriate timing and frequency to match typical six-step commutation used in BLDC motor control,
- No gate driver (IR2101) or motor model was included in this simulation, as the focus was solely on observing the PWM waveform patterns.

The transient analysis was run to observe the timing and shape of each PWM signal. The simulation confirmed that the signals had a consistent square waveform, with proper phase shifts of 120° between each phase pair, and an appropriate duty cycle for motor control.

This simulation served as a basic validation of the PWM timing logic and confirmed that the control signals are suitable for switching the MOSFETs in the full driver circuit.

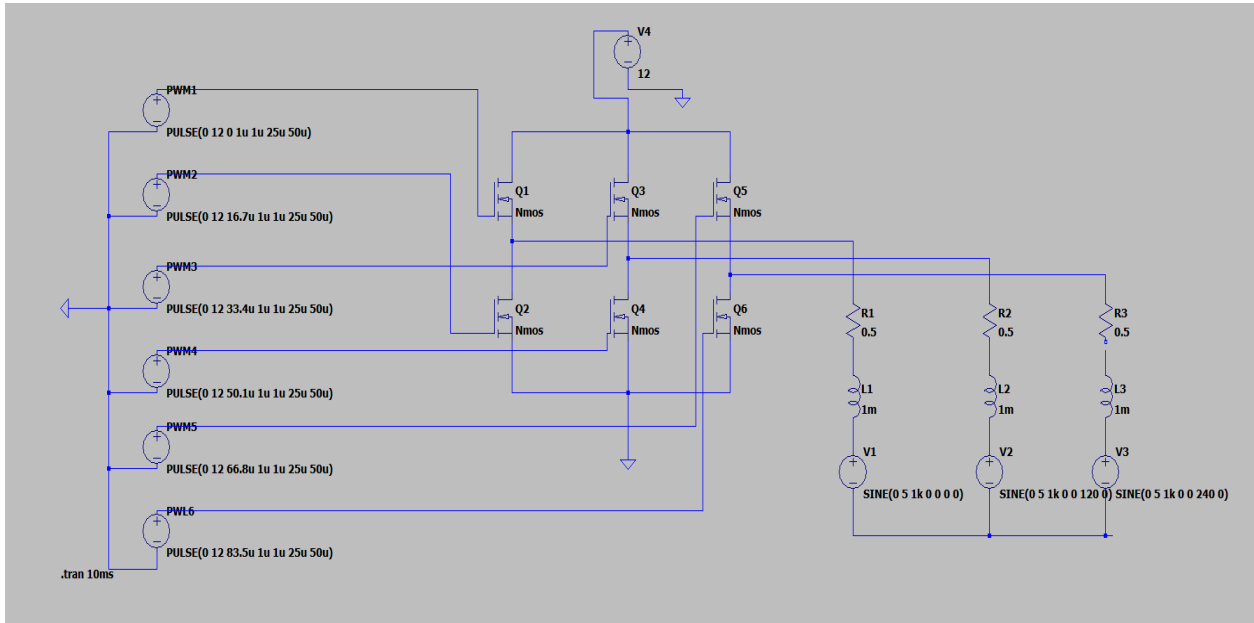


Figure 13. Simulation Circuit

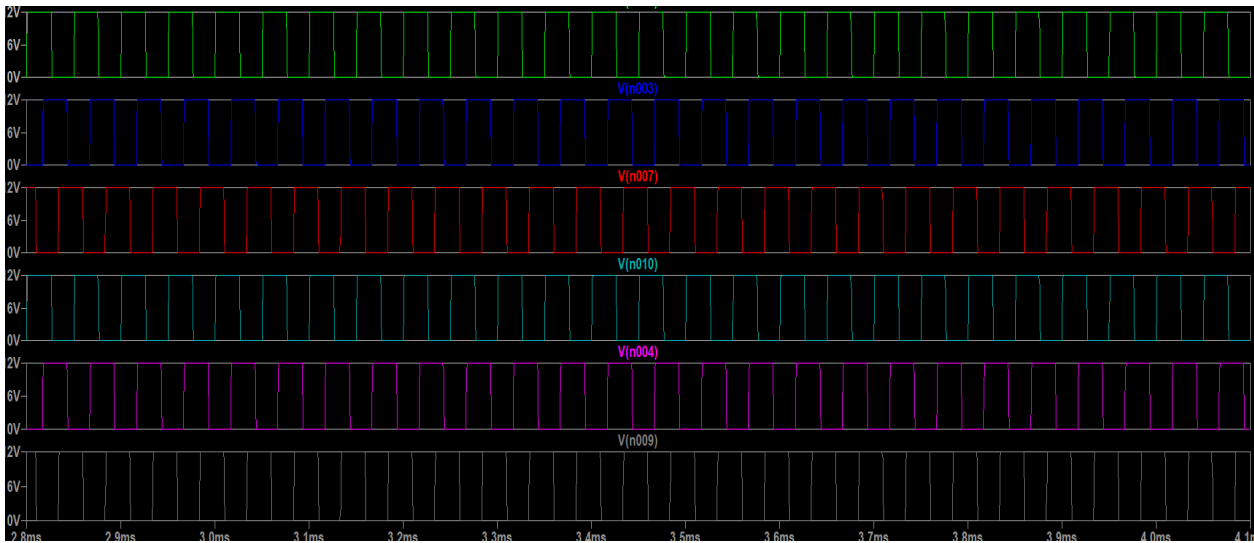


Figure 14. PWM Waveform

4.3 Arduino Programming

The Arduino code used in this project implements a basic sensorless BLDC motor controller using six-step (trapezoidal) commutation. The microcontroller used is the Arduino Uno, which directly controls the MOSFET switching using PWM signals generated through hardware timers. Sensorless control is achieved by detecting the Back Electromotive Force (Back-EMF) zero-crossings using the analog comparator built into the ATmega328P.

The code begins by initializing the relevant digital pins (3, 4, 5, 9, 10, and 11) as outputs, which are connected to the gates of the MOSFETs in the three-phase inverter. Two buttons connected to analog pins A0 and A1 allow the user to increase or decrease the motor speed by adjusting the PWM duty cycle. The PWM is generated using Timer1 and Timer2 hardware modules for precise signal control on pins 9, 10, and 11.

The core logic of commutation is executed in the analog comparator interrupt service routine (ISR(ANALOG_COMP_vect)), which is triggered whenever the monitored phase's Back-EMF crosses zero. Each time the interrupt is triggered, the motor steps to the next commutation state via the `bldc_move()` function. This function determines which MOSFET pair to activate based on the current step and also selects the appropriate comparator input for the next zero-crossing detection.

During startup, the motor is manually stepped through the six commutation states in open-loop mode to build initial rotation until it reaches a sufficient speed for Back-EMF detection. Once started, the analog comparator interrupt is enabled for sensorless operation.

PWM duty is dynamically adjusted using the `SET_PWM_DUTY()` function, which updates the compare registers (OCR1A, OCR1B, OCR2A) controlling the PWM output for each active high-side switch.

This code demonstrates a simple and cost-effective method for sensorless BLDC motor control using an Arduino, requiring minimal external components while still enabling reliable six-step commutation.

```

1  /* Sensorless(BLDC) motor control with Arduino UNO.
2
3  */
4
5
6  #define SPEED_UP          A0          // BLDC motor speed-up button
7  #define SPEED_DOWN       A1          // BLDC motor speed-down button
8  #define PWM_MAX_DUTY     255
9  #define PWM_MIN_DUTY    50
10 #define PWM_START_DUTY   100
11
12 byte bldc_step = 0, motor_speed;
13 unsigned int i;
14 void setup() {
15     DDRD  |= 0x38;          // Configure pins 3, 4 and 5 as outputs
16     PORTD = 0x00;
17     DDRB  |= 0x0E;          // Configure pins 9, 10 and 11 as outputs
18     PORTB = 0x31;
19     // Timer1 module setting: set clock source to clkI/O / 1 (no prescaling)
20     TCCR1A = 0;
21     TCCR1B = 0x01;
22     // Timer2 module setting: set clock source to clkI/O / 1 (no prescaling)
23     TCCR2A = 0;
24     TCCR2B = 0x01;
25     // Analog comparator setting
26     ACSR  = 0x10;          // Disable and clear (flag bit) analog comparator interrupt
27     pinMode(SPEED_UP,   INPUT_PULLUP);
28     pinMode(SPEED_DOWN, INPUT_PULLUP);
29 }
30 // Analog comparator ISR
31 ISR (ANALOG_COMP_vect) {
32     // BEMF debounce
33     for(i = 0; i < 10; i++) {
34         if(bldc_step & 1){
35             if(!(ACSR & 0x20)) i -= 1;

```

```

35         if(!(ACSR & 0x20)) i -= 1;
36     }
37     else {
38         if((ACSR & 0x20)) i -= 1;
39     }
40 }
41 bldc_move();
42 bldc_step++;
43 bldc_step %= 6;
44 }
45 void bldc_move(){          // BLDC motor commutation function
46     switch(bldc_step){
47     case 0:
48         AH_BL();
49         BEMF_C_RISING();
50         break;
51     case 1:
52         AH_CL();
53         BEMF_B_FALLING();
54         break;
55     case 2:
56         BH_CL();
57         BEMF_A_RISING();
58         break;
59     case 3:
60         BH_AL();
61         BEMF_C_FALLING();
62         break;
63     case 4:
64         CH_AL();
65         BEMF_B_RISING();
66         break;
67     case 5:
68         CH_BL();
69         BEMF_A_FALLING();
70         break;

```

```

69     break;
70 }
71 }
72
73 void loop() {
74     SET_PWM_DUTY(PWM_START_DUTY); // Setup starting PWM with duty cycle = PWM_START_DUTY
75     i = 5000;
76     // Motor start
77     while(i > 100) {
78         delayMicroseconds(i);
79         bldc_move();
80         bldc_step++;
81         bldc_step %= 6;
82         i = i - 20;
83     }
84     motor_speed = PWM_START_DUTY;
85     ACSR |= 0x08; // Enable analog comparator interrupt
86     while(1) {
87         while(!(digitalRead(SPEED_UP)) && motor_speed < PWM_MAX_DUTY){
88             motor_speed++;
89             SET_PWM_DUTY(motor_speed);
90             delay(100);
91         }
92         while(!(digitalRead(SPEED_DOWN)) && motor_speed > PWM_MIN_DUTY){
93             motor_speed--;
94             SET_PWM_DUTY(motor_speed);
95             delay(100);
96         }
97     }
98 }
99
100 void BEMF_A_RISING(){
101     ADCSRB = (0 << ACME); // Select AIN1 as comparator negative input
102     ACSR |= 0x03; // Set interrupt on rising edge
103 }

```

```

103 }
104 void BEMF_A_FALLING(){
105     ADCSRB = (0 << ACME); // Select AIN1 as comparator negative input
106     ACSR &= ~0x01; // Set interrupt on falling edge
107 }
108 void BEMF_B_RISING(){
109     ADCSRA = (0 << ADEN); // Disable the ADC module
110     ADCSRB = (1 << ACME);
111     ADMUX = 2; // Select analog channel 2 as comparator negative input
112     ACSR |= 0x03;
113 }
114 void BEMF_B_FALLING(){
115     ADCSRA = (0 << ADEN); // Disable the ADC module
116     ADCSRB = (1 << ACME);
117     ADMUX = 2; // Select analog channel 2 as comparator negative input
118     ACSR &= ~0x01;
119 }
120 void BEMF_C_RISING(){
121     ADCSRA = (0 << ADEN); // Disable the ADC module
122     ADCSRB = (1 << ACME);
123     ADMUX = 3; // Select analog channel 3 as comparator negative input
124     ACSR |= 0x03;
125 }
126 void BEMF_C_FALLING(){
127     ADCSRA = (0 << ADEN); // Disable the ADC module
128     ADCSRB = (1 << ACME);
129     ADMUX = 3; // Select analog channel 3 as comparator negative input
130     ACSR &= ~0x01;
131 }
132
133 void AH_BL(){
134     PORTD &= ~0x28;
135     PORTD |= 0x10;
136     TCCR1A = 0; // Turn pin 11 (OC2A) PWM ON (pin 9 & pin 10 OFF)
137     TCCR2A = 0x81; //

```

```

137     TCCR2A = 0x81; //
138 }
139 void AH_CL(){
140     PORTD &= ~0x30;
141     PORTD |= 0x08;
142     TCCR1A = 0; // Turn pin 11 (OC2A) PWM ON (pin 9 & pin 10 OFF)
143     TCCR2A = 0x81; //
144 }
145 void BH_CL(){
146     PORTD &= ~0x30;
147     PORTD |= 0x08;
148     TCCR2A = 0; // Turn pin 10 (OC1B) PWM ON (pin 9 & pin 11 OFF)
149     TCCR1A = 0x21; //
150 }
151 void BH_AL(){
152     PORTD &= ~0x18;
153     PORTD |= 0x20;
154     TCCR2A = 0; // Turn pin 10 (OC1B) PWM ON (pin 9 & pin 11 OFF)
155     TCCR1A = 0x21; //
156 }
157 void CH_AL(){
158     PORTD &= ~0x18;
159     PORTD |= 0x20;
160     TCCR2A = 0; // Turn pin 9 (OC1A) PWM ON (pin 10 & pin 11 OFF)
161     TCCR1A = 0x81; //
162 }
163 void CH_BL(){
164     PORTD &= ~0x28;
165     PORTD |= 0x10;
166     TCCR2A = 0; // Turn pin 9 (OC1A) PWM ON (pin 10 & pin 11 OFF)
167     TCCR1A = 0x81; //
168 }
169
170 void SET_PWM_DUTY(byte duty){
171     if(duty < PWM_MIN_DUTY)
172         duty = PWM_MIN_DUTY;

```

```

171     if(duty < PWM_MIN_DUTY)
172         duty = PWM_MIN_DUTY;
173     if(duty > PWM_MAX_DUTY)
174         duty = PWM_MAX_DUTY;
175     OCR1A = duty; // Set pin 9 PWM duty cycle
176     OCR1B = duty; // Set pin 10 PWM duty cycle
177     OCR2A = duty; // Set pin 11 PWM duty cycle

```

4.4 Hardware Setup

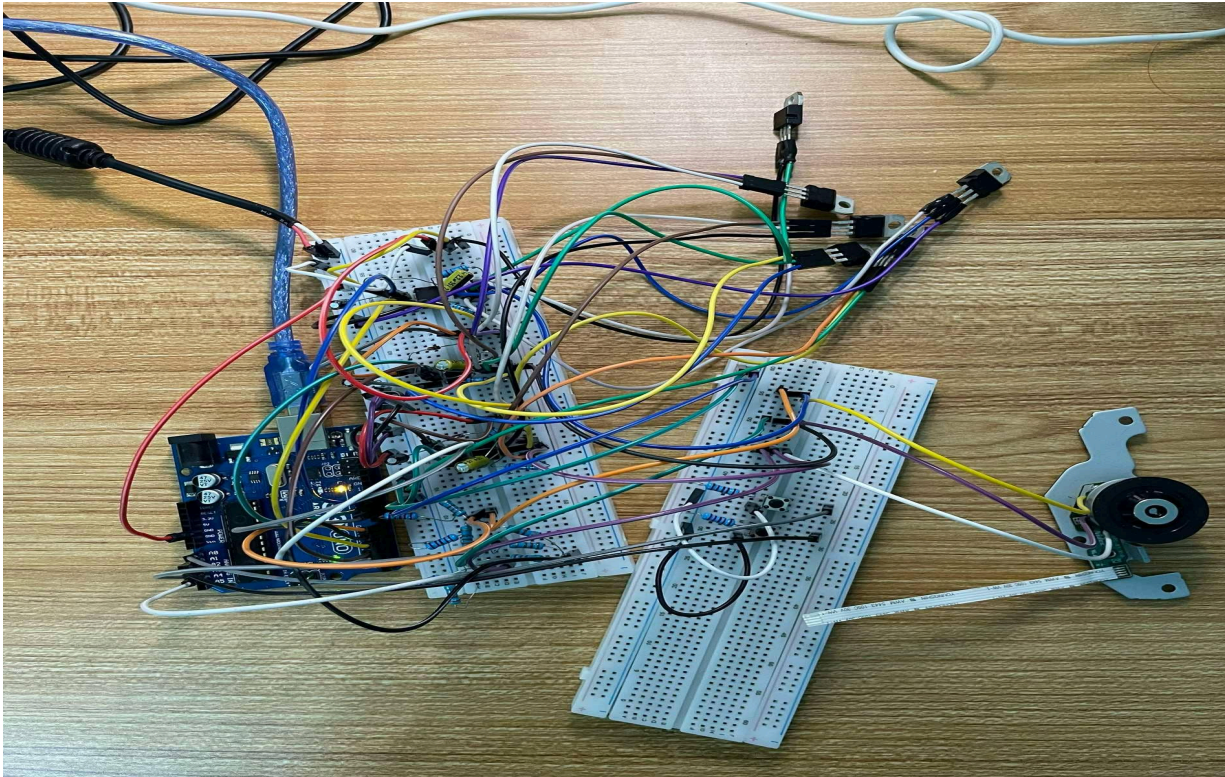
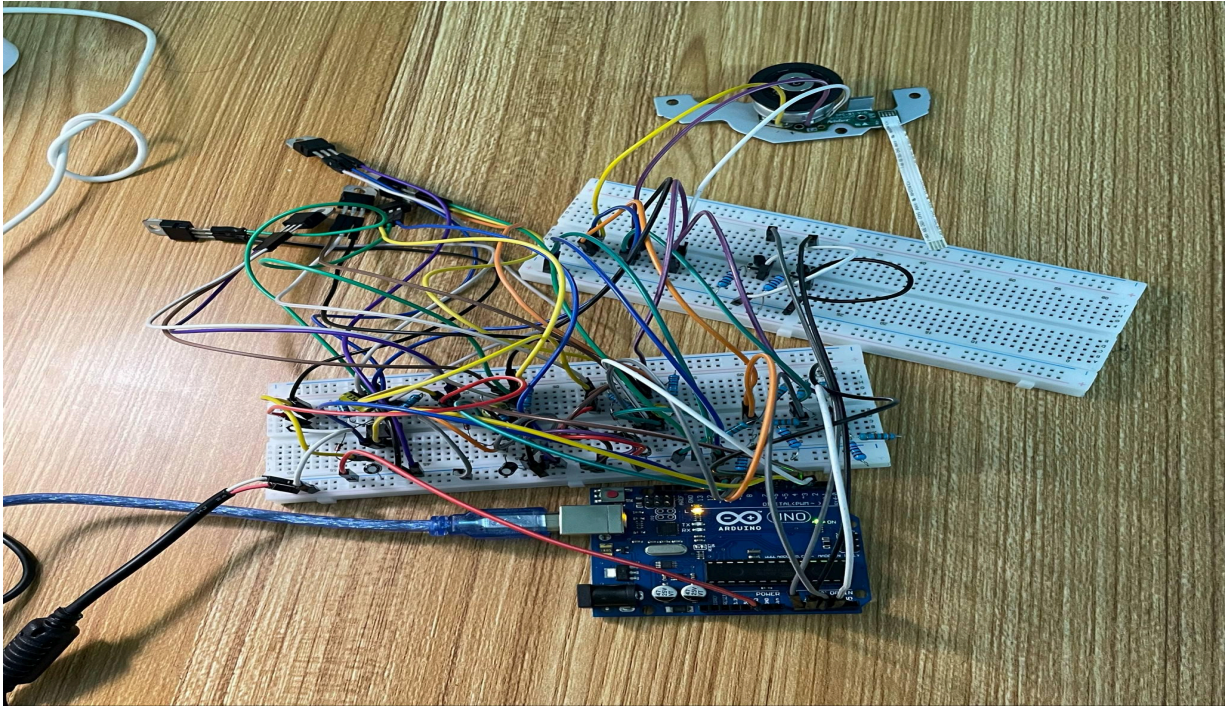


Figure 15. Whole Design Hardware Setup

5. CONCLUSION AND FUTURE RECOMMENDATION

Conclusion

This thesis presented the design and implementation of a sensorless BLDC motor controller intended for use in an impact wrench. The project was driven by the goal of independently building a working controller using basic components and hands-on methods, rather than optimizing for performance or efficiency. Through this process, key aspects of motor control and system design were explored and applied.

The controller was built around an Arduino Uno, programmed to generate the necessary PWM signals for commutating a three-phase BLDC motor. The IR2101 gate drivers and P75NF75 MOSFETs formed the core of the power stage, switching motor phases based on the logic signals from the Arduino. A sensorless control method was implemented by detecting the motor's back-EMF, eliminating the need for physical position sensors.

All stages of the design, including schematic drawing, component selection, and code development, were performed manually. This approach provided a valuable learning experience and allowed for a deeper understanding of how each part of the system works from microcontroller logic to power electronics.

While the controller is relatively simple and lacks advanced control features, it successfully demonstrates the core principles of sensorless BLDC motor operation. Overall, this project served as a meaningful exercise in practical electronics, control systems, programming and laid a solid foundation for more complex future work in the field of motor drives.

Future Recommendations

The current thesis focused on the basic design, simulation, and implementation of a sensorless BLDC motor controller for an impact wrench application using readily available components such as the Arduino Uno, IR2101 gate driver, and P75NF75 MOSFETs. While the project successfully demonstrated the fundamental control and operation of a BLDC motor, several improvements and extensions are recommended for future work:

1. Hardware Implementation and Testing

Although the simulation and circuit design were completed, full hardware testing with the actual motor and load (impact wrench mechanism) would provide more accurate insights into controller performance under real-world conditions. Future work should include building the prototype and testing torque, speed, and thermal performance.

2. Closed-loop Control Implementation

This project used a sensorless open-loop or basic zero-crossing detection method. Future work should consider implementing closed-loop control using feedback such as current sensing or estimated rotor position to improve torque control, efficiency, and dynamic response.

3. PCB Design and Optimization

A compact, noise-optimized PCB layout could enhance system reliability and EMI performance. Future iterations should focus on professional PCB design and possibly integration of all components into a single board suitable for industrial or commercial use.

4. Thermal and Efficiency Analysis

Future work should include detailed analysis of power losses, efficiency, and thermal management, especially since impact wrenches may draw high peak currents. Adding heatsinks, selecting more efficient MOSFETs, or using synchronous rectification techniques could be beneficial.

5. Mechanical Integration

Integrating the motor controller physically into the impact wrench casing and ensuring mechanical robustness, cooling, and safety under vibration and impact conditions is a critical area for future development.

By addressing these areas, future projects can develop a more robust, efficient, and commercially viable BLDC motor controller tailored for demanding applications like impact wrenches.

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