Senior Design Project Report

Six-Step Square-Wave Drive and Control for Electric Motors

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Introduction

Electric motors have become increasingly indispensable in modern society, with applications ranging from aerospace systems to underground exploration. To effectively analyze and utilize motor systems, a solid understanding of their operating principles is essential. Among various motor control strategies, six-step commutation plays a fundamental role in the operation of brushless DC (BLDC) motors.

A comprehensive understanding of six-step commutation enables proper motor drive implementation and lays the foundation for advanced control techniques. In this project, we focus on the operating principles and control strategies of six-step commutation. Using Code Composer Studio (CCS) for embedded programming, we implement fundamental motor control functions, including speed regulation and rotational direction control.

Motivation

After completing the course *Introduction to Electrical Engineering*, we gained a deeper understanding of the electromagnetic principles governing motor operation, including the interaction between windings and magnetic fields. The realization that electromagnetic forces can be harnessed to produce mechanical motion not only highlighted the elegance of motor design but also demonstrated its profound impact on technological advancement and modern life.

Upon entering the laboratory, we discovered that practical motor control is significantly more complex than simply applying a fixed voltage to drive rotation. In real-world applications, precise control requires coordinated switching of six power devices, along with advanced techniques such as enhanced pulse-width modulation (ePWM) for speed regulation.

To build a solid foundation in embedded motor control, we began by implementing basic LED control experiments to familiarize ourselves with CCS programming and microcontroller peripherals. After mastering these fundamentals, we integrated six-step commutation control to successfully drive and control the motor.

Principles of Six-Step Commutation Drive

Hall Sensors

Hall sensors serve as position detectors in motor systems. Their primary function is to identify the rotor position and provide real-time feedback signals for motor commutation.

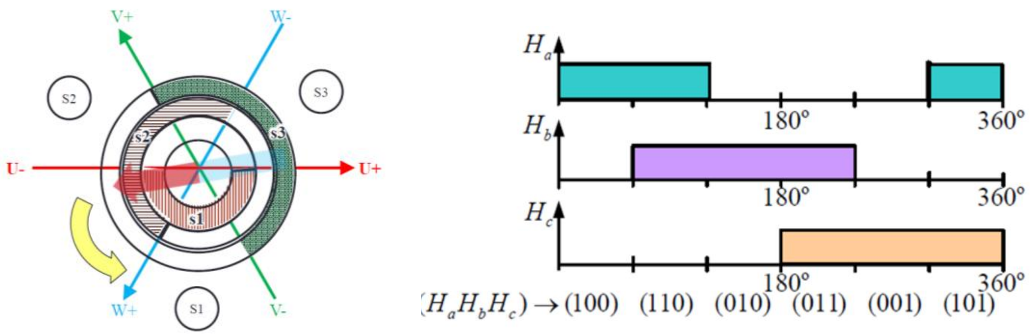

Figure 1. Hall Sensor Sector Distribution (Source: Yu-Chen Kuo, Department of Electrical Engineering)

As illustrated in Figure 1, three Hall sensors (S1, S2, and S3) are evenly distributed around the stator. Each sensor detects approximately 180 electrical degrees. When arranged in this configuration, the motor can be logically divided into six sectors, as shown in Figure 2. By interpreting the binary states of the three Hall sensors, the controller can accurately determine the rotor's current sector and execute the appropriate commutation sequence.

Mechanical Angle and Electrical Angle

The mechanical angle refers to the physical rotational angle of the motor shaft, where one full revolution corresponds to 360 mechanical degrees.

The electrical angle, however, depends on the number of magnetic pole pairs within the motor. Each pole pair corresponds to 360 electrical degrees.

For example, in a motor with two pole pairs, one mechanical revolution results in:

- **360 mechanical degrees**
- **720 electrical degrees**

Understanding the relationship between mechanical and electrical angles is critical for accurate timing of commutation and efficient motor operation.

Six-Step Commutation Drive

Six-step commutation is implemented using six switching devices (Q1–Q6), typically arranged as a three-phase inverter bridge. Each pair of switches energizes corresponding stator windings aligned with the U, V, and W phase axes.

The control process begins by reading the rotor position from the Hall sensors to determine the active sector. The controller then activates the appropriate pair of switches, generating a magnetic field that attracts the rotor toward the next sector.

By continuously repeating this sequence, a rotating magnetic field is produced, enabling sustained motor rotation.

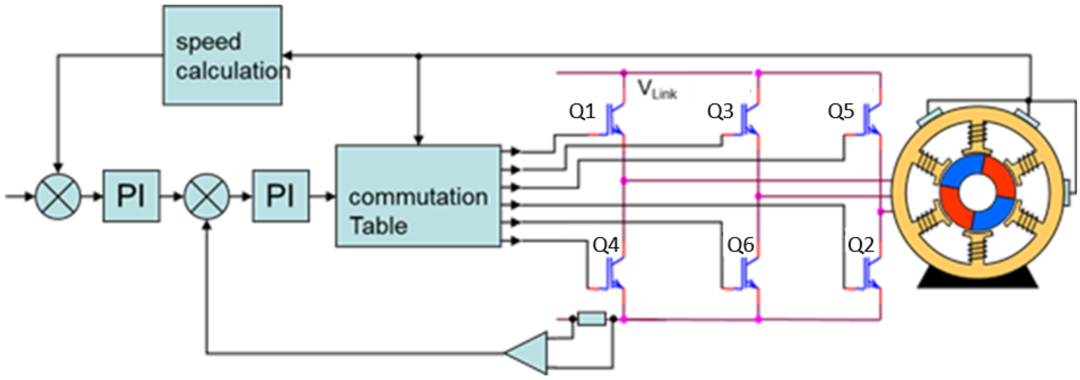

Figure 2. Switching Circuit Diagram (Adapted from Yu-Chen Kuo, Department of Electrical Engineering)

Torque Enhancement Through Hall Sensor Offset

The electromagnetic torque acting on the rotor can be expressed as:

$$\tau = r \cdot F \cdot \sin\theta$$

where r represents the moment arm, F denotes the applied force, and θ is the angle between the force vector and the rotor.

When the six sectors defined by the Hall sensors are perfectly aligned with the U–V–W phase axes, the angle θ within each sector varies from 90° to 30°, preventing the motor from consistently producing optimal torque.

To improve torque performance, the Hall sensors were mechanically shifted 30 degrees counterclockwise, as illustrated in the figure below. With this adjustment, θ varies from 120° to 60°, a range that is closer to the optimal torque-producing region.

This offset enhances torque generation and contributes to improved motor efficiency and dynamic response.

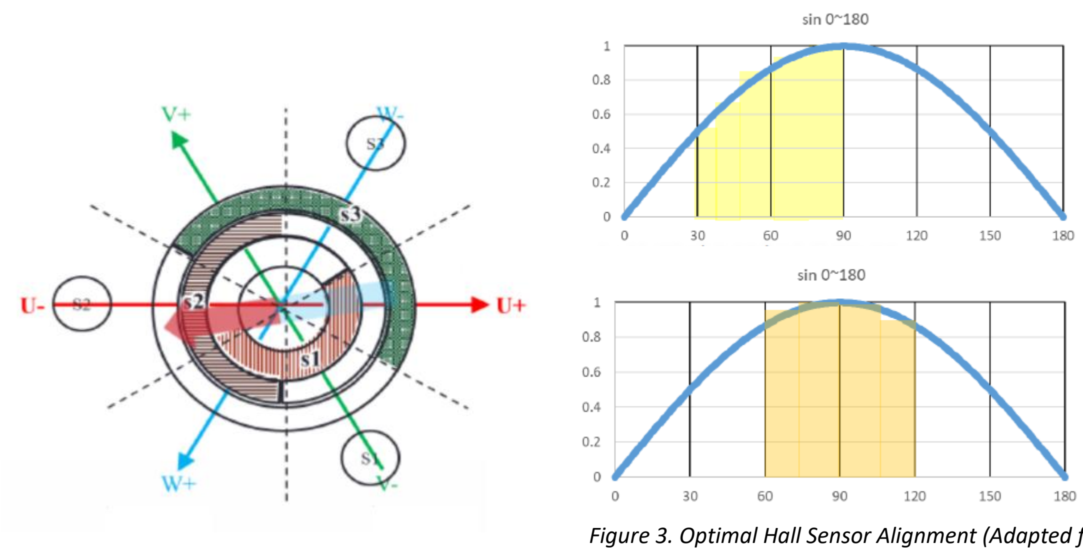

Figure 3. Optimal Hall Sensor Alignment (Adapted from Yu-Chen Kuo, Department of Electrical Engineering)

Methodology

Experimental Methodology

To establish the commutation sequence, the rotor was manually rotated to identify the corresponding Hall sensor signals for each sector. Based on these signals, forward and reverse drive lookup tables were constructed to control motor rotation.

A push-button interface was implemented to enable directional switching between forward and reverse operation. To prevent potential damage caused by abrupt direction changes, a protection mechanism was designed. Before reversing the rotation, the motor must first be brought to a complete stop by pressing a designated stop button. If the direction is switched without stopping the motor, the command is ignored to ensure operational safety.

Two control variables were defined to monitor the motor's rotational direction and stop status. The controller then referenced the predefined commutation tables to energize the appropriate switching devices and drive the motor accordingly. Experimental data were recorded for subsequent analysis.

Hardware Setup

For the electrical setup, the TI development board was powered by a 5V supply from the computer to provide control signals.

A laboratory power supply delivered:
20V for motor drive power
5V for gate driver control

The rated current limit was configured to 0.5 A to protect the hardware during operation.

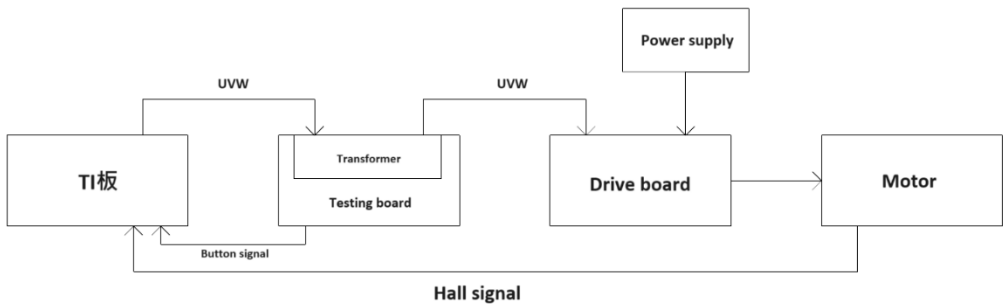

Figure 4. Control Flowchart

Experimental Procedure

Hall Sensor Validation

Prior to connecting the drive board, the Hall sensor signals were verified using the Code Composer Studio (CCS) Expression window, as shown in Figure 1. GPIO pins GPIO6–GPIO8, which were assigned to receive Hall sensor outputs, were monitored to confirm accurate detection of the rotor position.

According to the commutation table, the rotor sectors correspond to the following binary states:
001, 011, 010, 110, 100, 101, as illustrated in Figure 2.

Additionally, LEDs were used as visual indicators to validate the switching logic before integrating the drive board. This approach ensured that the switches were activated correctly based on rotor position while preventing short circuits caused by simultaneous activation of high-side and low-side switches on the same phase (shoot-through condition).

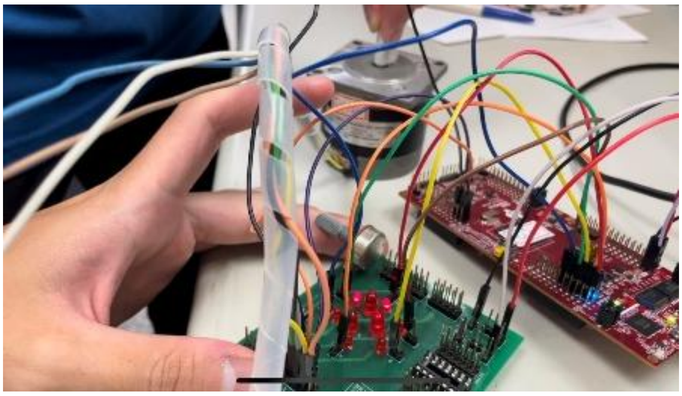

Figure 5. Motor Testing Setup

Commutation Table Development

Three Hall sensors, denoted as S1, S2, and S3, were installed inside the motor to detect rotor position. Since each Hall sensor covers 180 electrical degrees, the rotor position can be encoded into six distinct states:

001, 011, 010, 110, 100, 101

These states divide the motor into six sectors.The axes corresponding to each Hall sensor were defined as U+, U−, V+, V−, W+, and W−, with each axis representing a switching device in the inverter. Following the principles of six-step commutation, the axes were mechanically shifted 30 deg**rees counterclockwise** to better align with the torque-producing region, enabling the construction of the commutation table.

Operating Principle

The primary objective of the commutation table is to control the switching sequence so that electromagnetic torque is continuously generated to sustain motor rotation.

To achieve higher torque output, the optimal switching states for each rotor sector were identified. Based on vector superposition, simultaneously energizing two adjacent phases produces a resultant electromagnetic force located between the two phases.

By analyzing all six rotor positions, the appropriate switching pairs were determined for each state, allowing the commutation table to be systematically established, as illustrated in the figure below.

CW					
	GPIO6	GPIO7	GPIO8		
	S1	S2	S3		
1	0	0	1	V+	W-
2	0	1	1	U-	V+
3	0	1	0	W+	U-
4	1	1	0	V-	W+
5	1	0	0	U+	V-
6	1	0	1	W-	U+

CCW					
	GPIO6	GPIO7	GPIO8		
	S1	S2	S3		
1	0	0	1	V-	W+
2	0	1	1	U+	V-
3	0	1	0	W-	U+
4	1	1	0	V+	W-
5	1	0	0	U-	V+
6	1	0	1	W+	U-

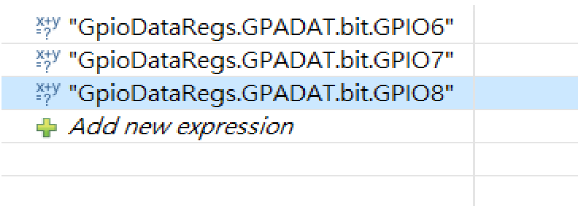

Figure 6. CCS Verification of Forward and Reverse Switching Signals

Power-On Testing

The control program was first uploaded to the Texas Instruments (TI) development board from a computer. Next, the 5V control supply was activated, followed by the 20V motor drive supply, after which the motor began operating normally.

To change the rotational direction, the stop button was pressed to bring the motor to a complete halt. Once the motor was fully stopped, the run button was activated to restart the motor in the opposite direction.

This power-up sequence ensured stable operation and prevented potential damage caused by abrupt directional switching.

Results and Discussion

At the start of the experiment, pressing the first button initiated reverse rotation, and the motor accelerated continuously. Pressing the second button brought the motor to a complete stop. When the first button was pressed again, the motor restarted in the forward direction and accelerated smoothly.

The experimental results confirm that the commutation table was correctly implemented, enabling stable bidirectional motor control. Continuous acceleration was achieved due to the electromagnetic torque generated during phase excitation, while the motor successfully stopped when all switching devices were turned off.

Additionally, it was observed that when an external force was applied to the rotor during operation, the supply current increased noticeably. This behavior aligns with motor characteristics, as greater torque demand requires higher current draw.

Discussion and Future Work

Based on the findings of this experiment, several potential directions for further research and system improvement were identified.

1. Speed Control Enhancement

The six-step commutation drive implemented in this project does not currently support speed regulation. By integrating enhanced pulse-width modulation (ePWM), the motor speed could be precisely controlled, enabling more flexible operation and improved performance.

2. Software Optimization

The current control program relies heavily on repeated code structures, frequently invoking the same registers with different parameters. Future improvements could include implementing state variables to represent operating conditions such as rotational direction and speed.

Once these variables are defined, conditional logic (e.g., if-based control) can dynamically adjust register parameters according to system states. This approach would significantly simplify the codebase while improving readability, scalability, and maintainability.