SPEED CONTROL OF PERMANENT MAGNET BRUSHLESS DC MOTOR

CHAN HAO JIE

UNIVERSITI SAINS MALAYSIA

2017

SPEED CONTROL OF PERMANENT MAGNET BRUSHLESS DC MOTOR

by

CHAN HAO JIE

Thesis submitted in fulfillment of the requirements for the degree of Bachelor of Engineering (Electrical Engineering)

JUNE 2017

ACKNOWLEDGEMENT

This final year project would not have been possible without the support and help of many people. I would like to express my deepest gratitude to my thesis supervisor, Dr. Dahaman Ishak for his time and patience throughout the project. His guidance helped me in all the time of project and writing of this thesis. His insightful suggestions, precious support and all the extra time poured in has resulted in the completion of this project.

My sincere thanks also go to all the assistant engineers in laboratory who helped me with the laboratories facilities. Without their precious support it would not be possible to complete this project.

A special thanks goes to PhD student, Tiang Tow Leong for his guidance in using and programming the Microchip PICDEM MC LV Development board. He also contributed valuable comments throughout the project. I would like to also thank my friend Goh Chong Teik who sacrificed his own time to design and fabricate a mounting hub for this project. His effort contributes to the completion of this project.

Last but not least, I would also like to thank my family who were always supporting and encouraging me during the completion of this project.

TABLE OF CONTENTS

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULT AND DISCUSSION

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

ADC	Analog-to-Digital Converter
CN	Change Notification
FOC	Field Oriented Control
IDE	Integrated Development Environment
ISR	Interrupt Service Routine
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PI	Proportional and Integral
PID	Proportional, Integral and Derivative
PM BLDC	Permanent Magnet Brushless DC
PMSM	Permanent magnet synchronous motor
SAR	Successive Approximation Register
TLBO	Teaching-Learning-Based Optimisation
UART	Universal Asynchronous Receiver Transmitter

KAWALAN KELAJUAN MOTOR ARUS TERUS MAGNET KEKAL TANPA BERUS

ABSTRAK

Motor Arus Terus Magnet Kekal Tanpa Berus (PM BLDC) popular dalam banyak aplikasi industri kerana ia mempunyai respons dinamik yang baik, jangka hayat operasi yang panjang, efisiensi yang tinggi dan lingkungan kelajuan yang luas. Projek ini bertujuan untuk membangun dan melaksanakan sistem kawalan gelung tertutup untuk mencapai kawalan laju motor PM BLDC dan menunjukkan respons dinamik yang baik. Sistem kawalan gelung tertutup ini direkabentuk dahulu dan kemudian dilaksanakan dalam Pemproses Isyarat Digital dsPIC30F2010 pada Papan Pembangunan PICDEM MC LV Microchip. Motor yang digunakan ialah motor PM BLDC enam kutub, tiga-fasa. Sistem ini diuji dengan tiga rujukan kelajuan yang berbeza dan rujukan kelajuan yang berubah-ubah untuk menilai prestasi dan tindak balas. Keputusan menunjukkan bahawa terdapat 6.7% lajakan apabila motor dikawal bermula dari sifar hingga 1000 rpm, dan tidak ada lajakan diperhatikan untuk 2000 rpm dan 3000 rpm. Respons juga menunjukkan bahawa kawalan kelajuan menghasilkan keputusan yang baik walaupun rujukan kelajuan berubah apabila motor sedang berpusing. Sistem kawalan kelajuan gelung tertutup memberikan keputusan yang memuaskan walaupun motor disambungkan dengan beban kipas.

SPEED CONTROL OF PERMANENT MAGNET BRUSHLESS DC MOTOR

ABSTRACT

Permanent Magnet Brushless DC motor (PM BLDC) is very popular in many industrial applications because of its good dynamic response, long operating life, high efficiency and wide speed range. This project aims to develop and implement a closed-loop control system to achieve PM BLDC motor speed control and to show good dynamic response. The closed-loop control system is first designed and then implemented inside a dsPIC30F2010 Digital Signal Processor on a Microchip PICDEM MCLV Development Board. The motor is a six-poles, three-phase PM BLDC motor. The system is tested with three different speed references and changing speed references to evaluate the motor performance and response. The results show that there is a 6.7% overshoot when the motor is controlled to run from zero to 1000 rpm, and no overshoot is observed for 2000 rpm and 3000 rpm. The response also shows that the speed control gives good result even if the speed reference is changed during motor operation. The closed-loop speed control system gives satisfactory result even when the motor is connected to a fan load.

CHAPTER 1

INTRODUCTION

1.1 Background

Permanent Magnet Brushless Direct Current (PM BLDC) motors have rapidly gained popularity in recent years. Compared to brushed DC motors and induction motors, PM BLDC motors have better torque-speed characteristics, better dynamic response, higher efficiency, longer operating life, noiseless operation, higher speed ranges and more robust construction [1], [2], [3]. The torque delivered to motor size ratio is also higher for BLDC motors, making them useful in application where space and weight are critical factors [3]. Thus, BLDC motors have been used in many applications such as automotive, aerospace, consumer, medical and instrumentation [2], [3].

The elimination of brushes in PM BLDC motors has overcome some of the major disadvantages of conventional brushed DC motors. The operating life and reliability of BLDC motors are better because there are no brushes and mechanical commutators to be serviced and replaced. Brushes in brushed DC motor tend to wear out and break during operation, thus requiring more maintenance. The speed range of PM BLDC motors is also higher because there is no mechanical limitation set by brushes. Arcs are produced in the brushes during high-speed commutation, causing power losses and also Electromagnetic Interference (EMI) [2]. In contrast, PM BLDC motors operate much more quietly and generate less electrical noise to nearby equipment.

PM BLDC motors have a flat speed to torque curve, which permits operation at all speed with rated load. The non-linear speed to torque curve of induction motors shows a lower output torque at lower speed [2]. PM BLDC motors are also more efficient because of the absence of current carrying conductors in the rotor [3]. The rotors of PM BLDC motors are commonly mounted or embedded with Neodymium-Iron-Boron permanent magnet materials, which allows the motors to have higher power density, lower rotor inertia and better dynamic response than induction motors [3].

Machine drives, which are primarily electric motors, fans and pumps, consume about 50% of the total electricity delivered to the manufacturing industries in the United States [4]. In Malaysia, 47% of the energy delivered to the industries is used by electrical motors [5]. This indicates that efficiency improvements to electrical machines can have a huge impact on the energy consumption of the industries [6]. PM BLDC motors are more efficient than brushed DC motors and induction motors, and if more PM BLDC motors are used, energy consumption and carbon emissions by the industrial processes can be reduced. Thus, by selecting a more efficient type of motors, the manufacturing industries can leave a smaller impact on the environment.

Speed control is an important aspect for applications such as robotics and automotive. Constant and accurate output speeds are expected from the PM BLDC motors under different loads. An open-loop speed control would not work satisfactorily because, under the effect of various loading conditions, the output speed of motors would vary. Therefore, a closed-loop speed control is important for such applications. The system would observe the output speed of the motors and adjust the input to the motors so that the output speed can reach the desired speed. A closed-loop speed control system can be easily implemented for PM BLDC motors because these motors require controllers for electronics commutation, and the speed control system can be installed inside the controllers as well.

1.2 Problem Statement

While a PM BLDC motor provides better performance compared to a traditional brushed DC motor [7], the motor needs to operate in a wide speed range accurately for it to be adopted in applications such as automotive and computers. Control algorithms might show good result in a simulation, but the real performance of the control system depends on a lot of factors, such as the sensors and control software [8]. Duma, et al. describe the implementation of a closed-loop motor control system on a microcontroller [9]. It is important to develop and verify a closed-loop control algorithm and system in a hardware implementation to control a PM BLDC motor. By developing the control system on a Microchip PICDEM MC LV Development Board, the performance and dynamic response of the system can be observed and evaluated.

1.3 Research Objectives

The main objective of this project is to control the running speed of a PM BLDC motor. The more specific objectives are as follows:

1. To develop the mathematical model for the operation of a PM BLDC motor.
2. To develop a closed-loop speed control for PM BLDC motor.
3. To conduct an experiment for validation and verification using Microchip PICDEM MC LV Development Board.

1.4 Scope of Research

The project focuses on the development and implementation of a closed-loop Proportional and Integral (PI) control system for the speed control of a PM BLDC motor. The PM BLDC motor is rated with an operating voltage of 24V and operating power of

135W. This project implements the control system using a dsPIC30F2010 Digital Signal Processor on a Microchip PICDEM MC LV Development Board.

1.5 Thesis Outline

This thesis consists of five main chapters from introduction to conclusion of this project. Chapter 1 consists of a brief background and explanation on PM BLDC motor, the problem statements, research objectives and scopes.

Chapter 2 presents a literature review of past research works related to the topic of this thesis. The application of PM BLDC requires precise and fast respond speed control, thus many control methods have been introduced and studied by researchers.

Chapter 3 first describes the mathematical equations that govern the operation of a PM BLDC motor. Then the chapter proceeds to explain the implementation of the closed-loop speed control system using a dsPIC30F2010 Digital Signal Processor, and performance evaluation of the system using a PM BLDC motor.

Chapter 4 discusses the results and findings from the closed-loop speed control. The step response of the system at different speed reference is analysed and discussed.

Chapter 5 presents the overall conclusion of this project. Summary of the outcomes, limitations and future works suggestions are covered in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Construction of a PM BLDC motor

A three-phase PM BLDC motor, like all other motor types consists of a stator and a rotor [10]. The non-moving or stationary part is known as the stator while the moving or rotating part is known as the rotor [10]. In most motors, the rotor is placed inside the stator, also called as an inner rotor motor. However, in some applications, having an outer rotor structure is more beneficial. This is known as external rotor motor, most commonly used as spindle motors for hard disk drives and as the drive motor for ventilation fans [10]. Only the more common inner rotor motor is discussed in sections below.

2.1.1 Stator

The stator of a PM BLDC motor is made up of laminated steel and stator windings. The windings are carried by the slots on the laminated steel. Most of the PM BLDC motors have three phase stator windings connected in star fashion [2]. Different types of back Electromotive Force (EMF) can be generated by different types of windings. There are two types of windings: trapezoidal and sinusoidal [2]. A trapezoidal winding gives a trapezoidal back EMF and a sinusoidal winding gives a sinusoidal back EMF as shown in Figure 2.1 and Figure 2.2. A PM BLDC motor has concentrated stator windings to give a trapezoidal back EMF while a permanent magnet synchronous motor (PMSM) has distributed stator windings to give a sinusoidal back EMF [8]. They are all categorised as permanent magnet ac motors, distinguished by their back EMF shapes.

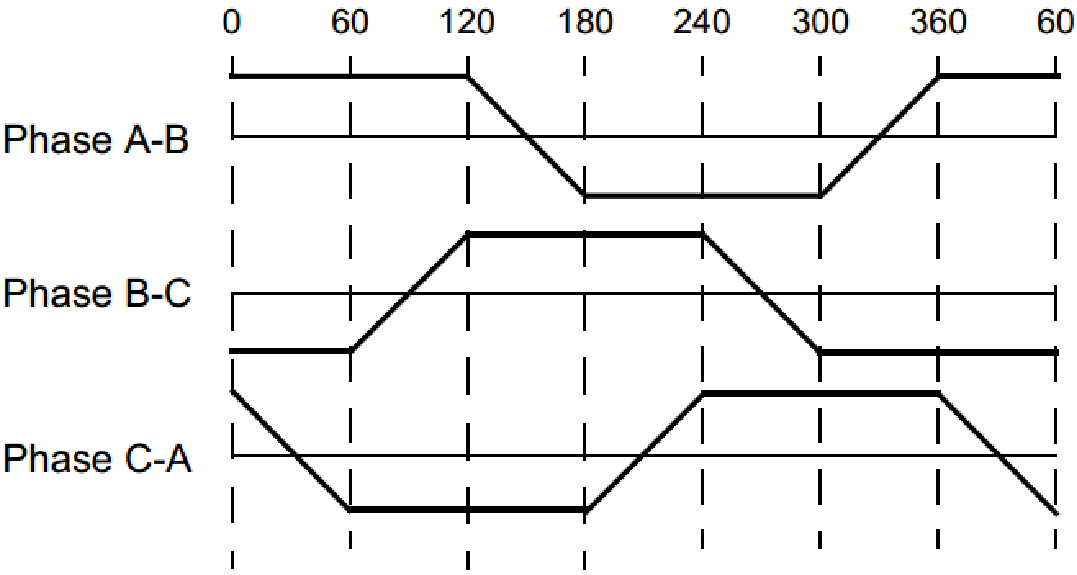

Figure 2.1 Trapezoidal back EMF [2]

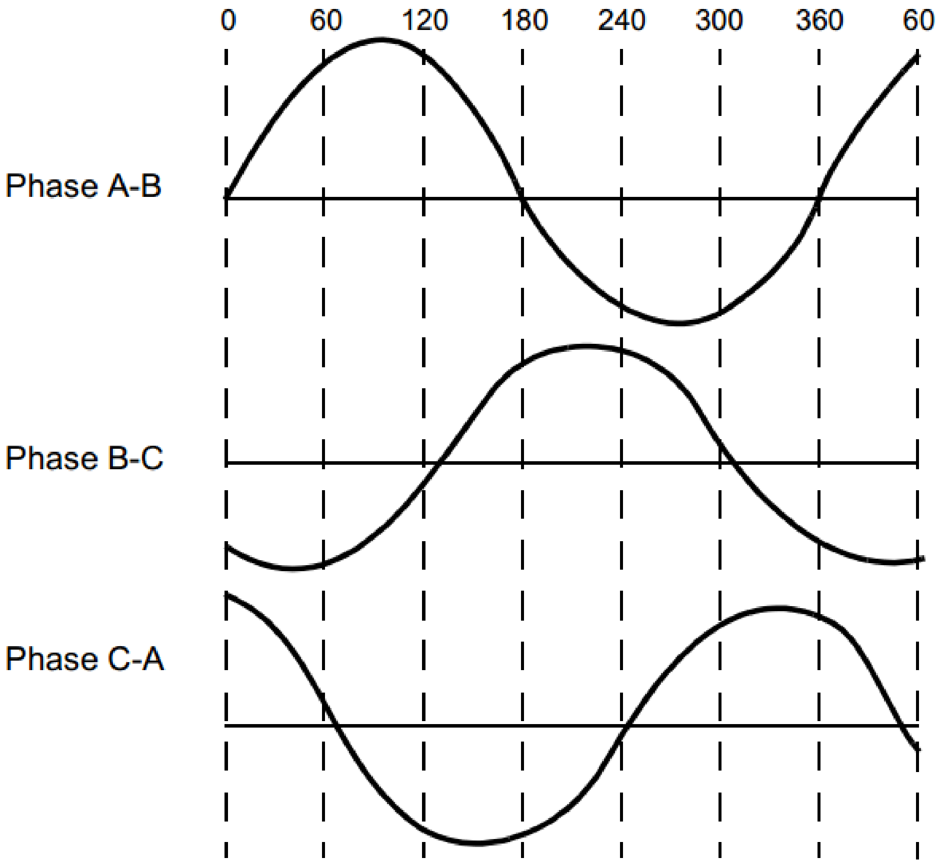

Figure 2.2 Sinusoidal back EMF [2]

2.1.2 Rotor

The rotor is fitted with permanent magnet materials such as NdFeB. The permanent magnets of the motors can be installed in different locations, which gives rise to several types of rotors. Finken, et al. studied and compared the performance of several rotor types shown in Figure 2.3. Figure 2.3(a) shows a surface mounted magnets rotor (SM-PMSM) [11]. The permanent magnets are mounted on the surface of the rotor. It is the simplest method to construct a PMSM, but the arrangement gives lower structural integrity and mechanical robustness [12] due to the centrifugal force acting on the rotor magnets during motor rotation. Thus, this arrangement is not suitable for high-speed applications [12]. Since the relative permeability of the magnet is approximately equal to air (1-1.05), SM-PMSM has almost uniform air gap, resulting in equal direct and quadrature axis inductances [12]. As a result, no reluctance torque is produced from this type of motor.

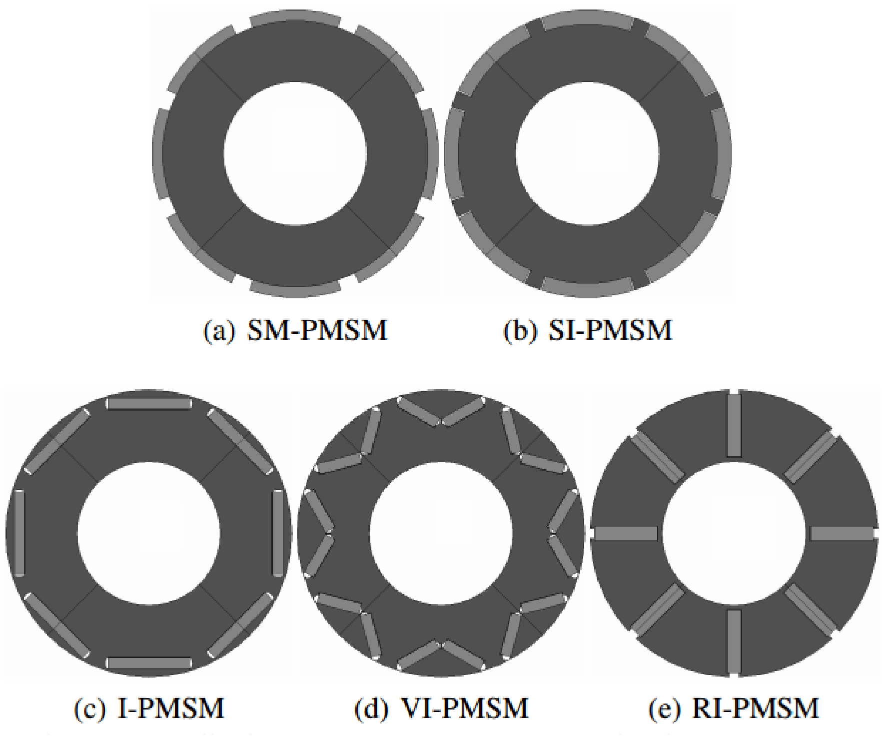

Figure 2.3 Permanent magnet motor rotor types [11]

If the permanent magnets are inset into the grooves of rotor surface, it is known as a surface inset magnets rotor (SI-PMSM) as shown in Figure 2.3(b). This arrangement is more robust mechanically, as the permanent magnets are fully embedded inside the rotor core giving the magnets mechanical support needed from flying out when the motor is rotating at high speed. Unlike SM-PMSM, SI-PMSM has a larger quadrature axis inductance [13]. This results in a greater reluctance torque produced.

Another type is that the permanent magnets are embedded in the interior of the rotor. This is known as interior PMSM. The construction of interior PMSM is more robust mechanically and therefore more suitable for high-speed applications. Figure 2.3(c), (d), (e) show different types of interior PMSM. Figure 2.3(c) shows an interior magnets rotor (I-PMSM), Figure 2.3(d) shows a V-shaped interior magnets rotor (VI-PMSM) and Figure 2.3(e) shows a radial-arranged internal magnets rotor (RI-PMSM). The ratio between quadrature and direct axes inductances can be larger than SI-PMSM and this results in even greater reluctance torque than SI-PMSM [12].

2.1.3 Hall Effect Sensor

A major difference between a brushed DC motor and a PM BLDC motor is the elimination of mechanical commutator and brushes. As a result, a PM BLDC motor is more efficient but it also needs an alternative way to perform its commutation. A PM BLDC motor generally performs its commutation electronically. The stator windings are energised in a sequence to rotate the stator field. It is very important for the controller to know the exact rotor position for it to determine which pair of windings to be energised. Most PM BLDC motors have three Hall Effect sensors embedded into the stator and the sensors can be used to detect the rotor position. Figure 2.4 shows the structure of an 8 poles PM BLDC motor.

Since the rotor is made up of permanent magnets, whenever the rotor magnetic poles pass through the Hall Effect sensors, they give a high or low signal, indicating either the North or South pole is passing through the sensors [2]. Based on the unique combinations of these signals, the controller can determine the exact commutation sequence. However, the Hall Effect sensors can be placed at 60º or 120º phase shift to each other based on their physical locations. The commutation sequence should be acquired from the manufacturer of a motor to ensure a successful control of the motor.

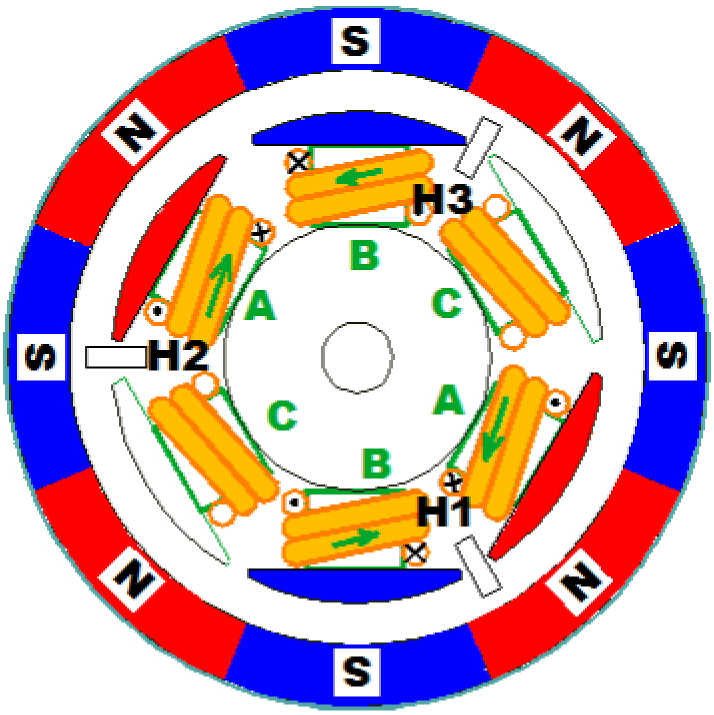

Figure 2.4 PM BLDC motor structure [14]

2.2 PMSM and PM BLDC Motor

As mentioned in the previous sections, a PMSM is a type of permanent magnet motor in which its stator windings are designed to give a sinusoidal back EMF, while a PM BLDC gives a trapezoidal back EMF. Torque is produced when the phase current flows into the back EMF source[10]. To produce an ideal torque, that is a constant torque without any torque ripple, the waveforms of the currents flowing into the back EMF source should be identical with the back EMF waveforms. Thus, a PM BLDC motor is usually driven using rectangular pulse currents [10]. This drive is often called as six step drive. A PMSM is typically driven by sinusoidal currents, whether it is through sinusoidal drive or modern Field Oriented Control (FOC) drive.

However, ideal rectangular pulse currents are impossible to be generated in physical world [10]. An ideal current pulse would require the transitions to be instantaneous but in reality, the transitions must take a finite amount of time. The non-ideal current pulses create torque ripple at every commutation points [10]. In a low-speed region, the torque ripple of a PM BLDC motor is around 4-5%, but the torque ripple problem becomes serious as the speed increases [13]. This is because at high-speed operation, the current cannot change as sharply as it was in the lower speed operation [13].

PMSM is better in speed and position accuracies, and it does not create torque ripple as PM BLDC motor [13]. But the main advantage of a PM BLDC motor over PMSM is its simplicity and cost. To drive a PM BLDC motor, the information needed by the controller to generate the correct commutation sequence can be obtained through the relatively cheaper Hall Effect sensors. To generate a sinusoidal current, the controller requires more accurate position information. This position information is traditionally provided by a resolver or optical encoder [10], which is more expensive [13].

FOC consists of controlling the stator currents represented by a vector. Thus, it is sometimes also known as Vector Control. The main attractiveness of this method is to control the flux and torque separately as it is in a DC machine [15]. Since the rotor field in a PMSM is established by permanent magnets, the flux component is not needed. Thus, only the torque component is needed to be controlled and it can be controlled in a conventional control loop.

2.3 Sensorless PM BLDC Motor Control

Traditionally, the rotor position is acquired through three Hall Effect sensors. The controller determines the commutation sequence through the unique combinations of the sensors' signals. However, the Hall Effect sensors would require regular maintenance and cleaning if a motor is operating in dusty or oily environments. Another type of control method known as sensorless control can eliminate the Hall Effect sensors by sensing the back EMF signals.

The most common implementation of sensorless control is back EMF zero-crossing technique shown in Figure 2.5. Provided that the motor speed is more than zero, the detection of back EMF zero-crossing is technically feasible. There are only two positions per electrical cycles where the back EMF of a phase is zero. The slopes of the back EMF through the zero crossing can be used to determine these two locations [16].

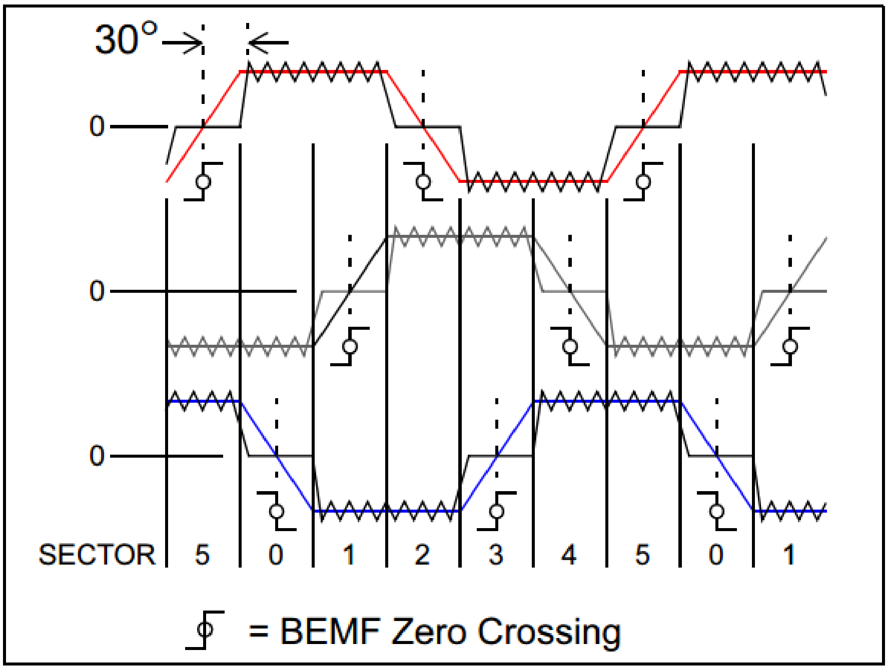

Figure 2.5 Zero crossing detection [16]

Generally, to implement this back EMF zero crossing method, a hardware implementation is needed to monitor all three phase terminal voltages and DC bus voltages using ADC via potential dividers. The correct sector should be monitored to detect the instant when the back EMF crosses one-half of the DC bus voltage. The commutation can be properly sequenced by calculating the time between two zero crossings, that is a 60º of an electrical cycle.

Because a back EMF is only generated when a motor is moving, sensorless control is difficult to run a motor at low speed, since the back EMF would be too small to be detected. Besides, when a motor is at standstill, it generates no back EMF. Alternate methods have to be used to start the motor. The back EMF can be estimated by injecting certain known pattern of voltages and detecting the current response [13]. By analysing the current responses, the rotor position can be estimated roughly.

2.4 Open-Loop Motor Control

D'Souza shows that a PM BLDC motor can be controlled in open-loop or closed-loop [17]. In the open-loop control, the Analog-to-Digital Converter (ADC) of a dsPIC30F2010 reads the voltage value of a potentiometer, and then this value is inserted as the duty cycle of the PWM output into the PM BLDC motor. The higher the duty cycle value, the higher the average value of voltage will be supplied to the motor and the faster it will spin. The simplicity of an open-loop system is suitable for an initial test of a PM BLDC motor. Rana, et al. show that an open-loop control using a dsPIC30F2010 is sufficient to control the speed of an axial flux permanent magnet motor [18].

2.5 Closed-Loop Motor Control

However, when there is a variation of load, an open-loop control is unable to maintain the motor's speed, thus renders it impractical in automotive and aerospace applications where speed control must be precise. D'Souza also presents a closed-loop control of a PM BLDC motor using a dsPIC30F2010 [17]. Instead of using the potentiometer's value as the duty cycle, the potentiometer's value is used as a speed reference. The actual speed of the motor is measured and an error signal is calculated. A PI controller will act on the error signal and generate the PWM signal needed to bring the motor's speed up to the speed reference. He concludes that the dsPIC30F2010 is well suited for a closed-loop control of a PM BLDC motor.

2.5.1 Proportional, Integral and Derivative (PID) Controller

PID and PI control are the traditional controller implemented for PM BLDC motor speed control [19]. PID control is simple and robust to be implemented using a microcontroller. Duma, et al. [20] present the minimal hardware requirements for a low cost embedded PM BLDC motor controller using a Renesas microcontroller and PID with anti-windup algorithm. Similarly, Duma, et al. [9] present a PM BLDC motor controller implemented with Texas Instrument Stellaris LM3S8962 microcontroller. The PID parameters tuning is completed using the relay feedback method. Potnuru, et al. [8] present a rapid prototyping method of implementing a PID control loop using MATLAB/Simulink block and dSPACE DS1103 controller board. They implement a hysteresis current controller inside the PID speed control loop and conclude that the approach shows good result.

One important step to achieving a good response in a PID controller is to tune the parameters. In a PID controller, each Proportional, Integral and Derivative component has a gain to be tuned. Traditionally, Ziegler-Nichols method is used for parameters tuning, as shown in [8]. In recent years, some new algorithms have been developed and have shown better results. Sharma and Gupta [21] show a new algorithm named Teaching-Learning-Based Optimisation (TLBO) can produce a better dynamic performance for speed controlling a PM BLDC motor than basic algorithms like Particle Swarm Optimisation and Linear-Quadratic Regulator.

2.5.2 Intelligent Fuzzy Controller

While the conventional PID controller can achieve good speed control within a specific range, the fixed control parameters are not suitable for a larger range of torque varying application [19], [22], [23], [24], [25], [26]. Jing, et al. [24] demonstrate that a conventional PID control shows weaker dynamic response to a step input, but better static response, while a fuzzy controller shows better dynamic response but worse static response. They propose a compound control, namely the fuzzy-PID control to give better dynamic and static response. Devi, et al. [23] also show the performance difference between a PIC controller and self-tuning fuzzy PID controller. The simulation shows that the output speed settled at 5.5 sec using a PID controller while the output speed settled at 4 sec using a fuzzy PID controller.

However, Devi, et al. [23] do not mention the type of controller the team implemented using a dsPIC30F4011 Digital Signal Processor, and they conclude that a speed control of PM BLDC can be achieved by PID. Only Jing, et al. [24] show the hardware implementation of a fuzzy-PID controller, the other teams [19], [22], [23], [25], [26] show the comparisons and differences in Matlab/Simulink environment. Kommula and Kota [19] show a huge performance improvement when a Hybrid Fuzzy PI controller is used instead. The Hybrid Fuzzy PI controller shows only 0.9% of peak overshoots while the conventional PI controller shows 4.1%. On the other hand, Kiruthika, et al. [22] demonstrate there is an improvement in settling time from 0.133s to 0.119s when using fuzzy PID controller, but the improvement in percentage overshoot is only from 5.65% to 5.45%. Guangxing, et al. [26] show some improvement in settling time when a fuzzy PI controller is used, but the result also shows a larger torque ripple when the load torque increases suddenly at t=0.1s.

2.6 Summary

This chapter provides a literature review on past research works related to speed control of a PM BLDC motor. The construction of a PM BLDC motor is discussed. The major parts are the stator, rotor and the Hall Effect sensors. Another type of PM AC motor, a PMSM is also introduced and compared with a PM BLDC motor. Their differences in back EMF shapes, control methods and performance are also discussed. Sensorless motor control, which is a control method without the Hall Effect sensors is explained. Finally, open-loop motor control and closed-loop motor control are discussed.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the design process of implementing a closed-loop speed control system for a PM BLDC motor. The chapter starts with a brief explanation on project design flow. The methodology can be divided into four parts: mathematical modelling of a PM BLDC motor, understanding the commutation of a PM BLDC motor, setting up the hardware required and then finally the development of source code for the closed-loop speed control.

3.2 Project Design Flow

The project starts with literature review on related works and theoretical backgrounds. Then, a mathematical model of a three-phase PM BLDC motor is developed to understand its operation. After that, the commutation sequence of the PM BLDC motor is studied and analysed. The next process is the development of the source code for the actual implementation of a closed-loop speed control system on a microcontroller.

After making sure the control system can run the motor successfully, further testing and experimental measurements are carried out. The responses of the system under different conditions are measured and recorded. Voltages and current waveforms of the motor are also recorded. The overall project design flowchart is shown in Figure 3.1.

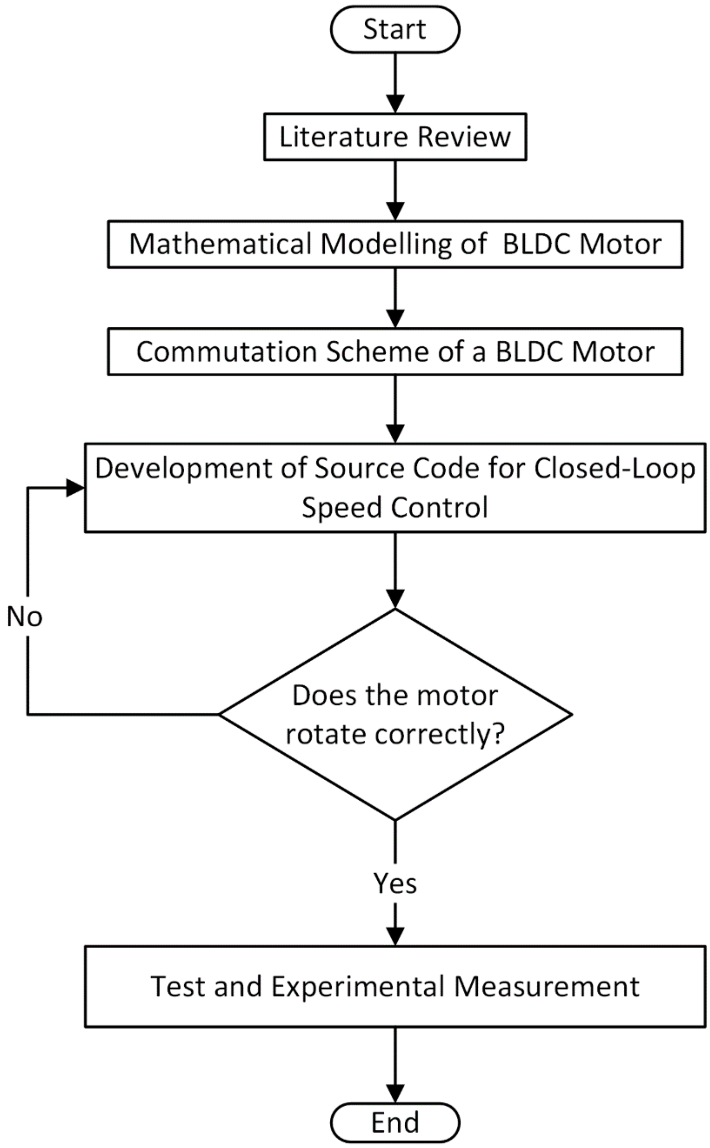

Figure 3.1 Project Design Flowchart

3.3 Mathematical Modelling of Three-Phase PM BLDC Motor

The mathematical model of a PM BLDC motor is important for its control system design. The equivalent circuit of a PM BLDC motor is shown in Figure 3.2.

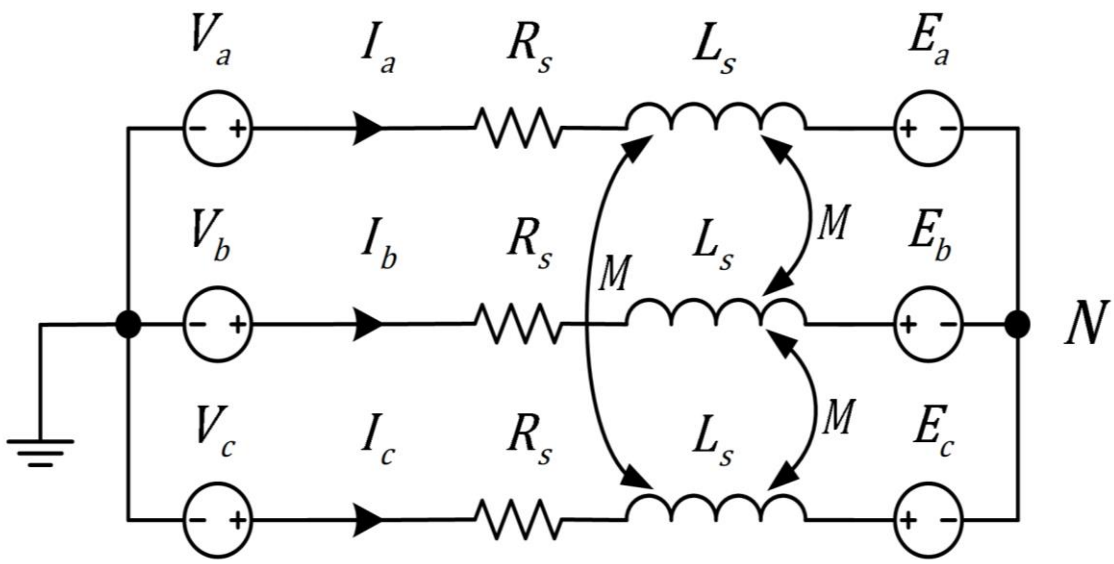

Figure 3.2 PM BLDC motor equivalent circuit

The phase resistances of the stator windings are assumed to be equal, rotor inductances are constant with the rotor angle, rotor-induced current is neglected and damper windings are not included in the model. The three-phase voltage equations are shown in equation (3.1) [27].

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \tag{3.1}$$

where:

V_a, V_b, V_c : Phase voltages,

I_a, I_b, I_c : Phase currents,

E_a, E_b, E_c : Phase back-EMFs,

R_s : Phase resistance,

L_s : Self-inductance,

M : Mutual-inductance.

The electromagnetic torque is

$$T_e = \frac{E_a I_a + E_b I_b + E_c I_c}{\omega_m} \tag{3.2}$$

where ω_m is the mechanical speed of the rotor.

The equation of motion is given by

$$\frac{d\omega_m}{dt} = \frac{T_e - T_L - B_{\omega_m}}{J} \tag{3.3}$$

where:

T_L: Load torque,

B_{ω_m}: Damping constant,

J: Moment of inertia of rotor shaft and load.

3.4 Commutation Scheme of a PM BLDC Motor

PM BLDC motor is a type of synchronous motor. The rotor field rotates synchronously, or in other words, at the same frequency with the stator field generated by the stator windings. To generate a rotating stator field, the stator windings are energised in a predefined sequence. This is the basis of six-step commutation.

However, if the stator field rotates faster than the capability of the rotor field to follow, the rotor will go out of sync with the stator field and the rotor will just vibrate instead of rotating. Thus, it is important for the controller to obtain the rotor position information so that it can energise the correct pair of phase windings to create the maximum torque.

3.4.1 Six-Step Commutation

Figure 3.3 shows a simplified 2 poles PM BLDC motor with its phase winding current paths. The 3-bits codes shown around the peripheral of the motor represent the outputs from the Hall Effect sensors when the North Pole of the rotor points in that direction. The Most Significant Bit is Hall Effect sensor C and the Least Significant Bit is Hall Effect sensor A.

The combination of the Hall Effect sensors' outputs will theoretically give 8 statuses from 000 to 111. However, for a sensor placement of 120º electrically apart from each other, signal 000 and 111 are ignored or not used. They are instead used for checking fault condition from the sensors. The controller should stop the motor if signal 000 and 111 are detected. The remaining six codes divide the 360º electrical cycle into 6 sectors. The exact point where the code changes state is the position that the stator magnetic field should be changed.

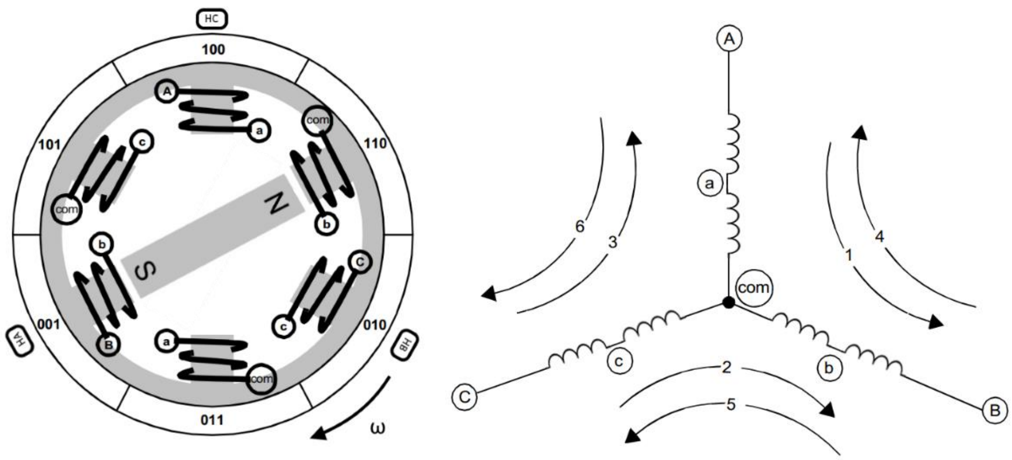

Figure 3.3 Simplified PM BLDC motor

In this motor, the three windings are Y-connected at a common point. Most PM BLDC motors have a three-phase Y-connected windings. A motor with this topology is driven by energising two phases at the same time. Thus, there are six different current paths for the motor.

In order to rotate the rotor, the phases that will produce the most amount of torque should be energised. The maximum torque is obtained when the rotor is 90º electrical away from the alignment with the stator magnetic field. Commutation for the rotor position in Figure 3.3 would be following current path 3 for a clockwise rotation.

The rotor position in Figure 3.3 is in sector 110. Figure 3.4 shows the same rotor position, with the additional labelling of rotor and stator field. The rotor field is indicated by the red arrow while the resultant stator field is indicated by the blue arrow. The maximum torque to rotate the rotor in clockwise direction can be created by energising phase C and A such that current flows from phase C windings into phase A windings. This is also shown as current path 3.

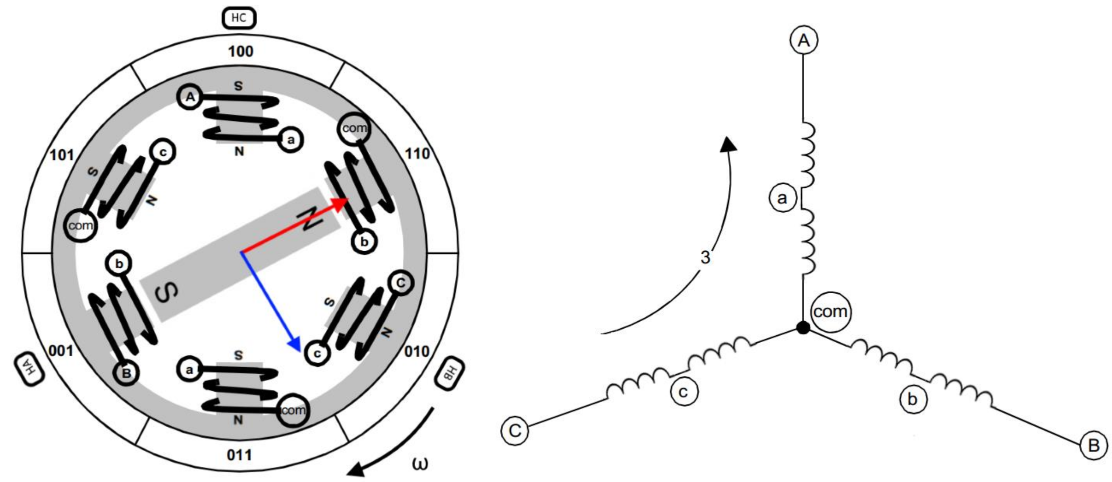

Figure 3.4 PM BLDC motor commutation in sector 110

When the rotor reaches the next sector, sector 010, another pair of windings are energised as shown in Figure 3.5. The commutation follows current path 4, where phase B and phase A are energised such that current enters phase B windings and exits through phase A windings. The resultant stator field is once again 90º from the rotor field to keep the rotor running after the stator field.

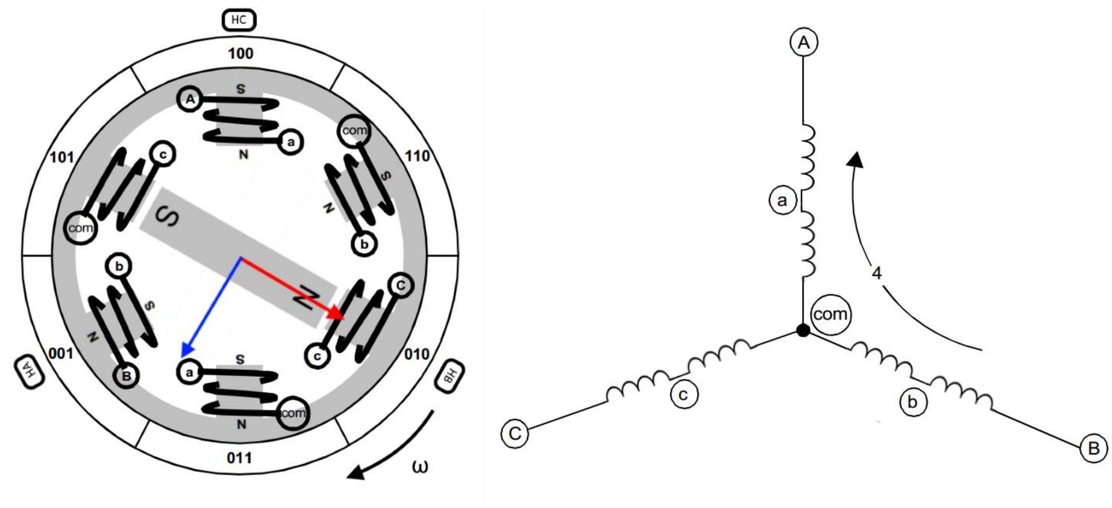

Figure 3.5 PM BLDC motor commutation in sector 010

Thus, the windings are energised in a sequence that follows current path 1 to 6. The sequence will create a rotating stator field in six discrete steps for one complete electrical 360º. For the simplified motor in Figure 3.3, one mechanical revolution is the same as one electrical revolution. PM BLDC motors can have more than two poles, such as the six-poles motor used in this project. For a six-poles motor, one mechanical revolution is equivalent to three electrical revolutions.

3.4.2 Commutation Table

A table can be constructed to specify which two phase windings should be energised to produce the maximum torque at that particular rotor position. Table 3.1 shows the sequence of the commutation based on the Hall Effect sensors inputs for a clockwise rotation. 'DC+' means the phase terminal is connected to the positive voltage of the DC bus and current flows into that phase winding, while 'DC-' means the phase terminal is connected to the negative voltage of the DC bus and current flows out of that phase. 'Off' means no voltage is applied to the phase terminal.

Table 3.1 Commutation table

Phase	Sensor C	Sensor B	Sensor A	Phase A	Phase B	Phase C
1	1	0	1	DC+	DC-	Off
2	1	0	0	Off	DC-	DC+
3	1	1	0	DC-	Off	DC+
4	0	1	0	DC-	DC+	Off
5	0	1	1	Off	DC+	DC-
6	0	0	1	DC+	Off	DC-

Each switching sequence consists of one motor terminal driven high, one motor terminal driven low, and one motor terminal left floating. Figure 3.6 shows the inverter circuit implemented on the Microchip PICDEM MC LV Development Board. There are three pairs of MOSFETs (Metal Oxide Semiconductor Field Effect Transistor), each controlling the power flowing into one phase of a PM BLDC motor. When a particular gate signal is HIGH, the MOSFET switches on and conducts.

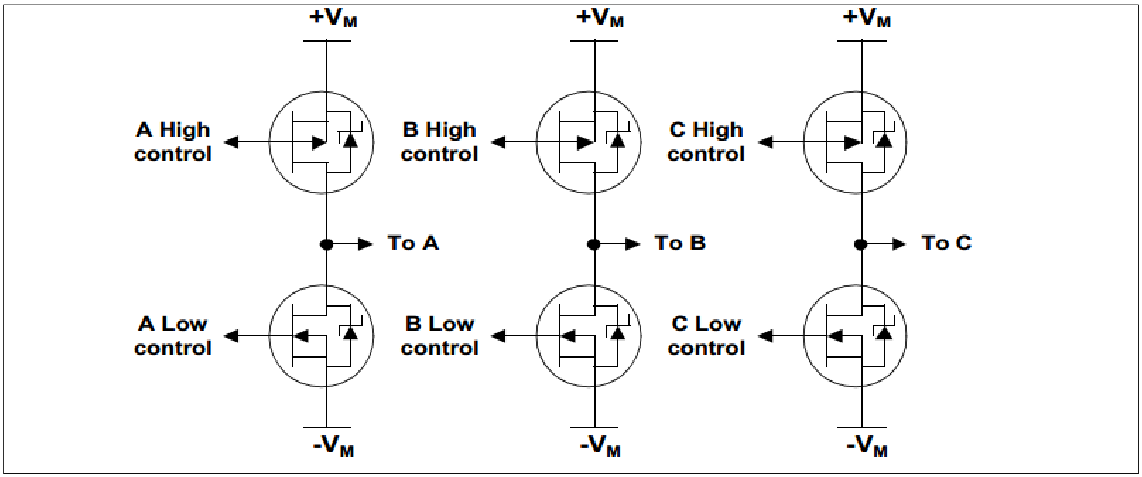

Figure 3.6 Three-phase inverter circuit [28]

Table 3.2 shows the sensor and gate drive signals linking the Hall Effect sensor state with the corresponding drive state. When the high side MOSFET conducts, the terminal is connected to the DC bus positive voltage, when the low side MOSFET conducts, the terminal is connected to the DC bus negative voltage. Thus, the high and low side MOSFETs from the same phase should not conduct at the same time or the DC bus would experience a short-circuit condition.

Table 3.2 Sensor and gate drive signal [28]

Phase	Sensor C	Sensor B	Sensor A	C High Drive	C Low Drive	B High Drive	B Low Drive	A High Drive	A Low Drive
1	1	0	1	0	0	0	1	1	0
2	1	0	0	1	0	0	1	0	0
3	1	1	0	1	0	0	0	0	1
4	0	1	0	0	0	1	0	0	1
5	0	1	1	0	1	1	0	0	0
6	0	0	1	0	1	0	0	1	0

Figure 3.7 shows the relationship between the sensor outputs and the motor drive voltages. Referring to the example above in Figure 3.4, phase A shows V- voltage while phase C shows V+ voltage in sector 110.

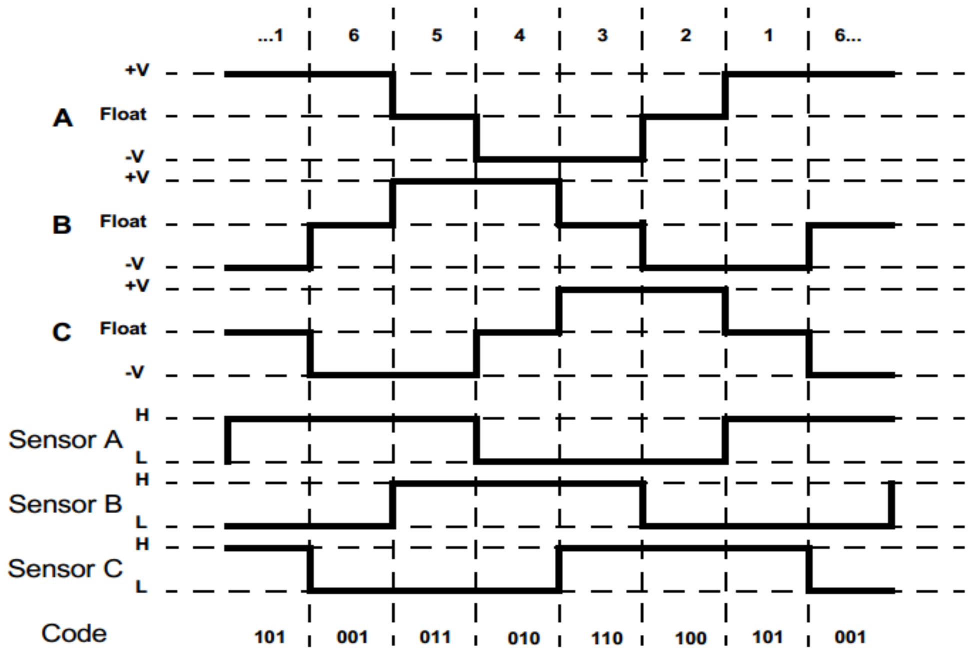

Figure 3.7 Sensor outputs and the drive timing [28]