Investigation of Position Control with Brushless DC Motors

by

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15359

Dissertation submitted in partial fulfilment of

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CERTIFICATION OF APPROVAL

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Approved by,

____

(Dr Ho Tatt Wei)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHD KHAIRILASYRAF BIN KAMARUDDIN

ABSTRACT

The purpose of this project is to investigate the possibility the of position control of Brushless DC Motor (BLDC). The conventional position control using optical encoder prove to be difficult as the high resolution optical encoder is hard to find due to lack of manufacturer to produce the optical encoder. The objective of this project is to investigate and study the position control of the BLDC. The method use in this project to achieve the objectives is by using the input from the build in hall sensor inside in the BLDC and also using the back-emf produce by the BLDC. In this report, the timeline of the project and the methodology is discussed. Also literature review is done in order to apply the position control of the BLDC. The methodology will discuss the overall project flow and also what had been done in order to achieve the objectives. In result and discussion, the result from the methodology is discuss and justified. Lastly the conclusion will conclude what had been achieved and what is need to be done in this project.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1:

INTRODUCTION

1.1 Background

Brushless DC (BLDC) motor is widely used in everyday life as the application from a household product to industrial use. BLDC motor has been use washing machine, air conditioner, water pump vacuum cleaner freezer, lathe machine and also use in the electric car.

The brushless construction makes it a preferred option compare to the brush DC motor because its reliability. This makes the BLDC machine more robust due to lack of mechanical commutator. That also make BLDC motor easier to maintain without need to change the motor brush at certain time. The robustness of the BLDC motor makes them very popular to use. Besides that, the BLDC work very silent due the fact that it not has a brush to commutate. Since the BLDC motor does not have a brush commutator, a switching circuit is required to commutate the motor. Without a switching circuit, it is impossible to commutate and later control the speed of the motor.

In BLDC Motor, torque is induced on the rotor by magnetic fields of time-varying polarity due to current-switched electromagnets. Hall-Effect sensors sense the orientation of the rotor. This signal is used by the controller to generate the time sequence of the switching current to induce torque. The BLDC motor also can use the back-emf signal from the motor to be use as the input to replace the Hall Effect sensor for motor commutation. The goal of this project is to investigate the possibility the hall sensors to command position movement.

1.2 Problem Statements

We wish to create a new position control technique for BLDC motor using the Hall Effect sensors and electronic switching circuitry of BLDC motors. But the available signal receives from the Hall Effect sensor still lack of accuracy for position control. The Hall Effect sensor can only be used for commutation and not suitable for position control due the lack of resolution it produced. The Hall Effect sensor also is not ideal to determine the position control as the maximum operating temperature is limited to 75℃.

As for the back electromotive force (back-emf), the signal has been used to detect the rotor position in order to excite the commutation of the BLDC. Although that is the case, the position control is limited to commutation only. The back-emf signal also is complicated. Its need to be filter because the signal produce is combines with the motor driver signal and also interrupted by noise.

Due to lack of accuracy in the Hall Effect sensor and also back-emf method the encoder is usually used in position control. The need of optical encoder for position control is not ideal due to its size and high cost. In this project we would like to avoid using traditional optical encoders. Although high resolution optical encoder is good for position control, the lack of manufacturer mean that is hard to get high resolution optical encoder with low cost.

1.3 Objectives and Scope of Study

In this project, there are two main objectives to be achieved:

1. To design an algorithm for position control of BLDC motors using Hall Effect sensors or sensorless control and switching circuitry.
2. Demonstrate and characterize the performance of this position command algorithm on a combination BLDC motors in a robot.

CHAPTER 2:

LITERATURE REVIEW/THEORY

2.1 Literature Review

Brushless DC Motor (BLDC)

Brushless DC Motor (BLDC Motor) design had significant different compare with the brushed DC motor (BDC). The stator of the BLDC is compromise of the magnet instead of the winding in the BDC and for the rotor the BLDC is the 3-phase winding compare to the permanent magnet in BDC. Due to the construction, BLDC motor needs an external commutation circuit to drive it. For the BLDC motor there is two type of winding of the stator, which is delta (Δ) and wye (Y) configuration. The major difference of the configuration is Y-configuration give high torque at low RPM, meanwhile the Δ-configuration produce low torque at low RPM. In the industry, BLDC had has been used widely due its reliability and also low maintenance of the motor [1]. This due to the design of the motor that eliminate the mechanical commutator that been used in brushed DC motor. This characteristic is suitable for critical application when current sparks interrupt the signal [2]. Instead using the mechanical commutator, BLDC motor used electronic commutator [3].

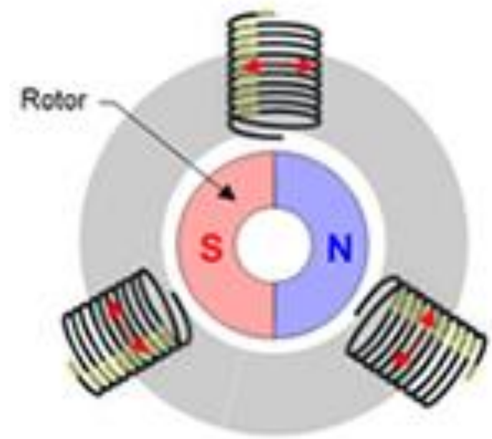


Figure 2.1: Two poles BLDC motor.

BLDC Motor Commutation

Since the BLDC motor do not have mechanical commutator, an electronic commutation is needed to drive the motor. The electronic commutator needs the input from the motor to determine the position of the rotor. There are two technique are normally used to sense the position of the rotor which is, Hall Effect sensor input and using the back-emf from the motor winding. As for the Hall sensor, some of the motor manufacturer already have a default Hall sensors inside the motor construction. For the Hall Effect sensing commutation technique, 3 Hall Effect sensors are needed to determine the rotor position. The 3 Hall Effect sensor the will give it's 6-steps output to the motor controller which is control the commutation [1]. For the back-emf sensing method, the controller determine the rotor position by using the back-emf value in each of the BLDC motor winding [4]. The value of the back-emf then compare with the neutral voltage of the motor. Noise proves to be challenge for this method during the BLDC motor operation due to necessity to compare with the neutral voltage [5]. Other control method for the electronic commutation also use sensorless control algorithm [6].

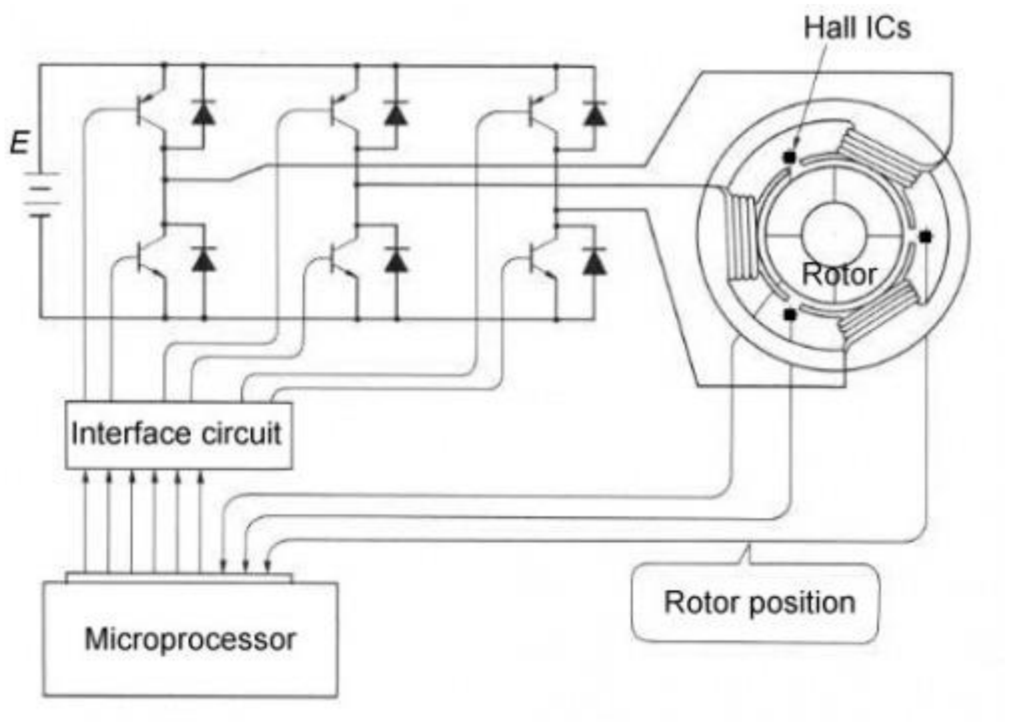


Figure 2.2: BLDC motor controller using Hall Effect sensor

Encoder

BLDC motor has been use in many position control application. For most position control applications, an optical encoder is needed in order to control the motor motion. The optical encoder will give feedback to the motor controller. There is several type of optical encoder such as quadrature encoder, gray code and standard binary code area usually used as position control. The accuracy of the optical encoder is determined by the resolution of the encoder. The optical encoder is not a default in BLDC. Normally it is attach externally to the motor shaft. The output of the encoder is in DC voltage. The output of the optical encoder is used as the input of the motor controller in order to achieve precise and accurate motion. Although optical encoder is reliable position controller, it is also expensive method for position control [6]. Besides that, the size of the motor also will be increase due to optical encoder and will create problem when space is limited [6]

Hall Effect Sensor

Hall Effect has been founded by E.H. Hall in 1879. Although the theory is more than 100 years, the application of Hall Effect only is noticeably used in 1950. The principle behind Hall Effect is when a current passes through a sample placed in a magnetic field, for example metal, a potential proportional to the current and to the magnetic field is developed across the material direction perpendicular to both the current and to the magnetic field[7]. The Hall Effect sensors work based on the Hall Effect principle. Most of the sensor used in the BLDC motor is digital sensor, when there is a positive magnetic field, the sensor will send a high signal to the motor controller. The positive magnetic field is from the south pole of the magnet. For the negative magnetic field is from the north pole of the magnet. Although there is a default Hall Effect sensor inside BLDC motor, the sensor only is used for the electronic commutation and not as position control. Hall Effect sensing is usually used in low cost application [8]. Hall Effect sensor although prove to be reliable, sometimes needed signal filtering [8]. It is because the Hall Effect sensor need to be in exact 120° of each other for accurate positioning [8]. The Hall Effect sensing also not suitable for application that expose to high temperature [5].

2.2 BLDC Motor Position Control Theory

For this project there is three methods that possible in order to achieve accurate motor control. The first method is to use Hall Effect sensor input to determine current motor position. This method also considering using an analog output or ration metric Hall Effect sensor. The analog output or ration metric Hall Effect sensor had different output depend on the proximity of the magnet and also depend on the position of the sensor. Since the output of the analog Hall Effect sensor is unique to its position, we can determine the position of the motor fairly easy. In order to achieve high accuracy the position of the sensor is vital to its signal integrity. A slight deviation in the position of the sensor can make the signal inaccurate.

The second method is to use the back-emf as input to the controller. Back-emf position control has been done recently by several researches but only to replace the Hall Effect sensor for the electronic commutation. The back-emf voltage value is measure during the rotation of the motor. A comparator is used at the each windings of the electronic commutator and will compare any back-emf value. Because of the unique back-emf value during the rotation, this value can be used as position control.

For the third method, the author wants to combine the Hall Effect sensor input and also the back-emf value of the BLDC motor. Due to the unique back-emf value and also reliability of the Hall Effect sensor, combining this two signal will produce a good reference for the position control.

With a precise and accurate measurement of the input, the position control is possible as it has a good and reliable input to track the motor magnet current position. The control algorithm use in microprocessor will use this outputs to control the rotation of the motor in order to achieve the position control.

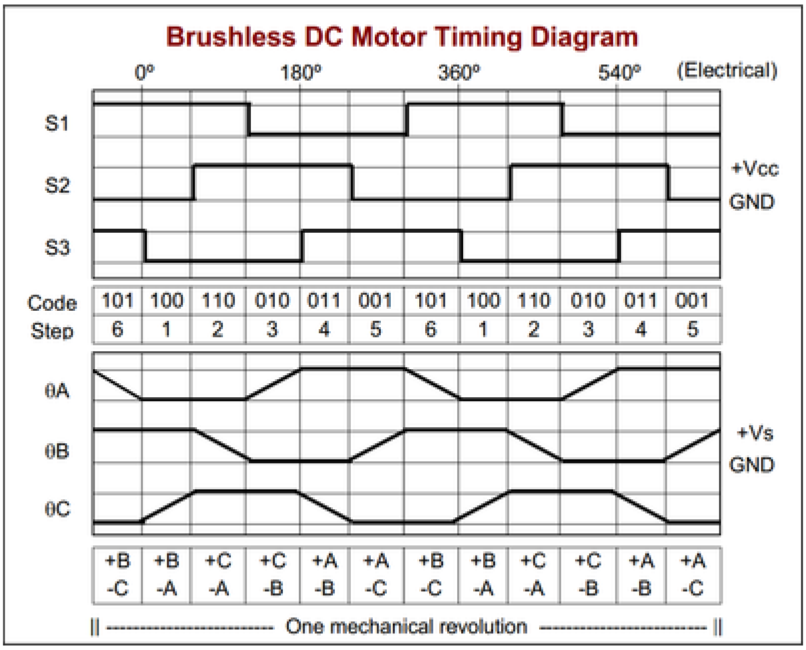


Figure 2.3: Hall Effect sensor output (top) and phase voltage (bottom)

CHAPTER 3:

METHODOLOGY/PROJECT ACTIVITIES

The methodology in this project can be classified into 3 separate subsections and each subsection outcome is important in order to achieve the objectives of this project. The first part of the methodology is project planning and execution. The second part of the methodology is study and determines the best approach to achieve position control. Last and the third part of the methodology are the strategy and development of the algorithm. All 3 subsections will produce a better overall project flow and kept the main objectives intact along the project period.

3.1. Project Planning and Execution

The first part of the methodology is project planning and execution. The outcome of project planning and execution is to make sure the project is on the right track and sufficient work is done. In this subsection the project timeline and project flow diagram are used to visualize and keep track of the project progress throughout the project period.

3.1.1. Project Timeline

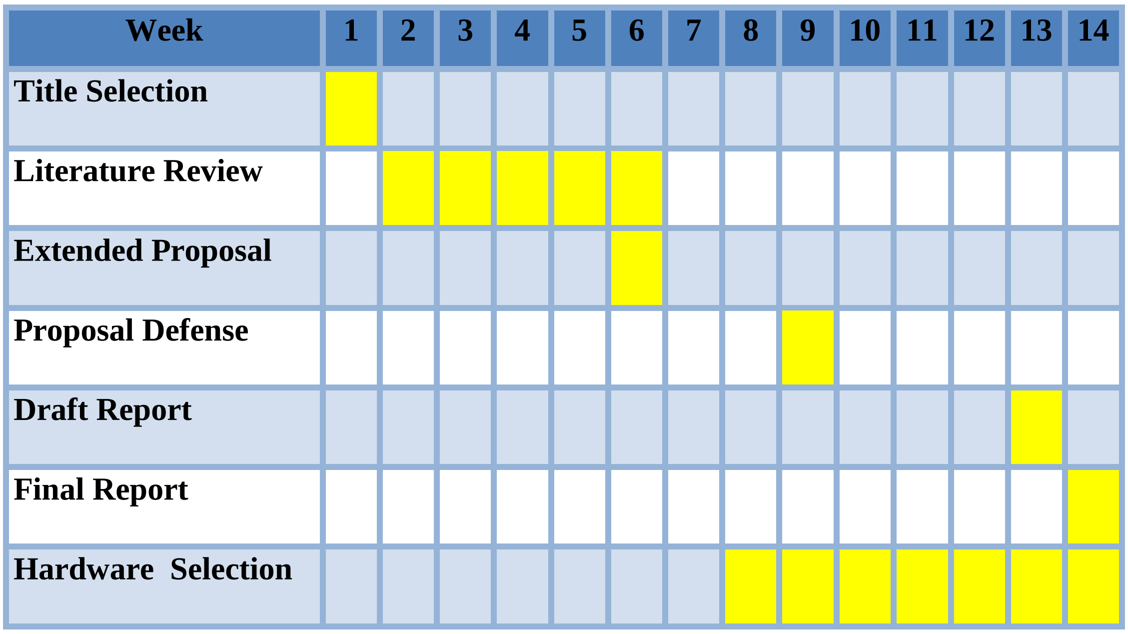


Figure 3.1: Gantt chart for FYP 1

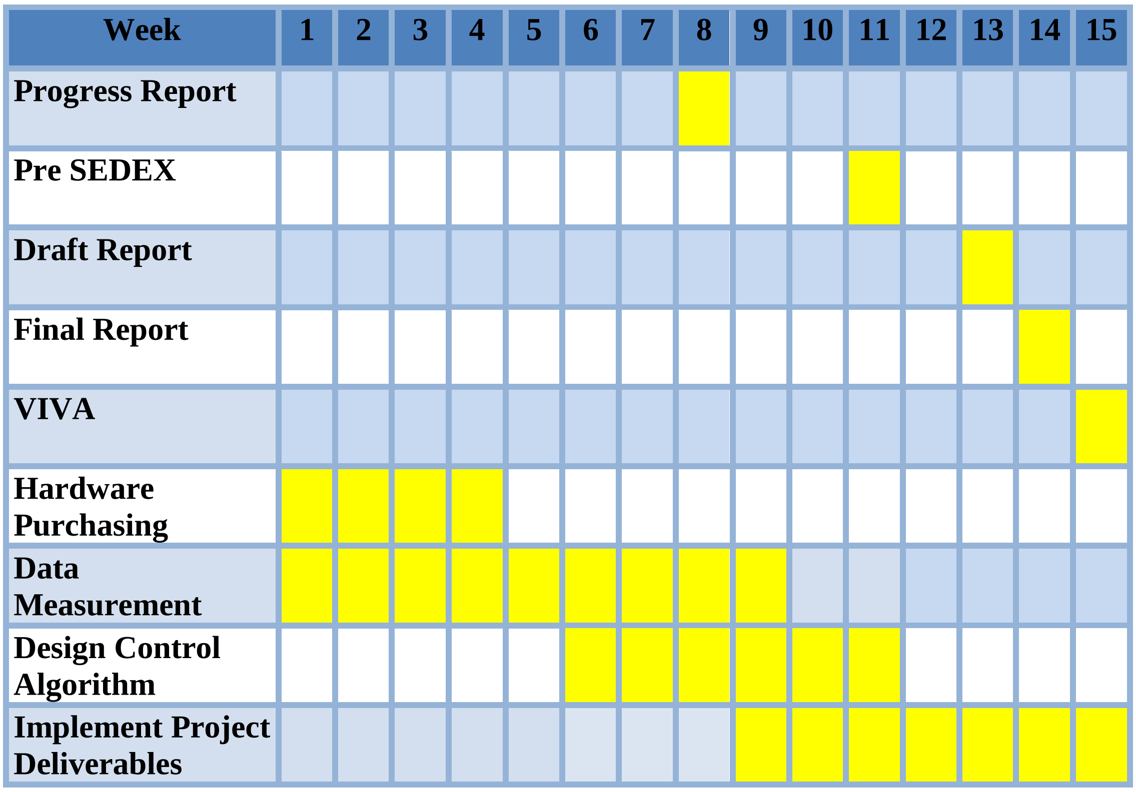


Figure 3.2: Gantt chart FYP 2

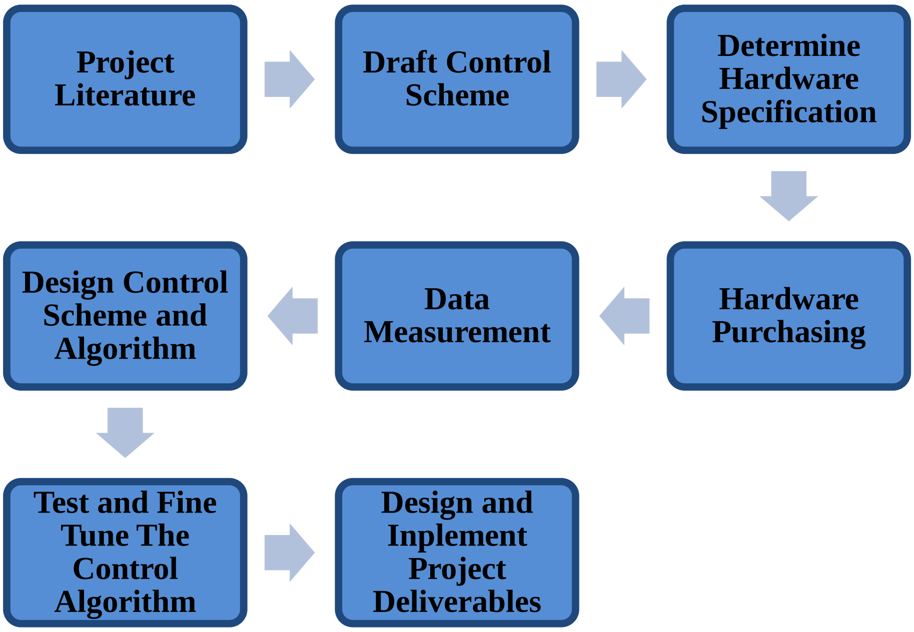


Figure 3.3: Project Flow Diagram

3.2. Determine The Overall Approach To BLDC Position Feedback

The second part of the methodology is study and determines the best approach to achieve position control by measuring the signal produce by the BLDC motor which is back-emf and also Hall Effect sensor output. Outcome of this part is to study the signal can be used to determine the rotor position of the motor. Since this project is novel, every possibility of the technique and approach is study in order to achieve the best approach and method in order to achieve position control.

3.2.1. Propose Control Scheme

There are 3 main control schemes and techniques that need to be study and explore. The 3 control schemes are using the digital Hall Effect sensor, using the back-emf and lastly using the analog Hall Effect sensor. Every technique mention have a different approach so this step will help to determine which is the best to be implement in this project in order to achieve the main objectives.

3.2.1.1. Using digital Hall Effect sensor as input to determine rotor speed and position.

For the control strategy, the output from the Hall Effect sensor can be used to determine the speed and also the rotor position. Besides that the speed of the rotor can be known using one of the Hall Effect sensors that count the rotation of the rotor than later is compute according to the clock speed of the microcontroller. The sensor element of the motor produces digital high level for 180 electrical degrees and low level for another 180 electrical degrees. The three sensors are offset 60 electrical degrees with each other. The relation

After the speed is known the PWM can be used to control the position of the rotor. PWM gives output according to the clock speed of the microcontroller. With the PWM as output control algorithm can be design along with the usable input from the Hall Effect sensor.

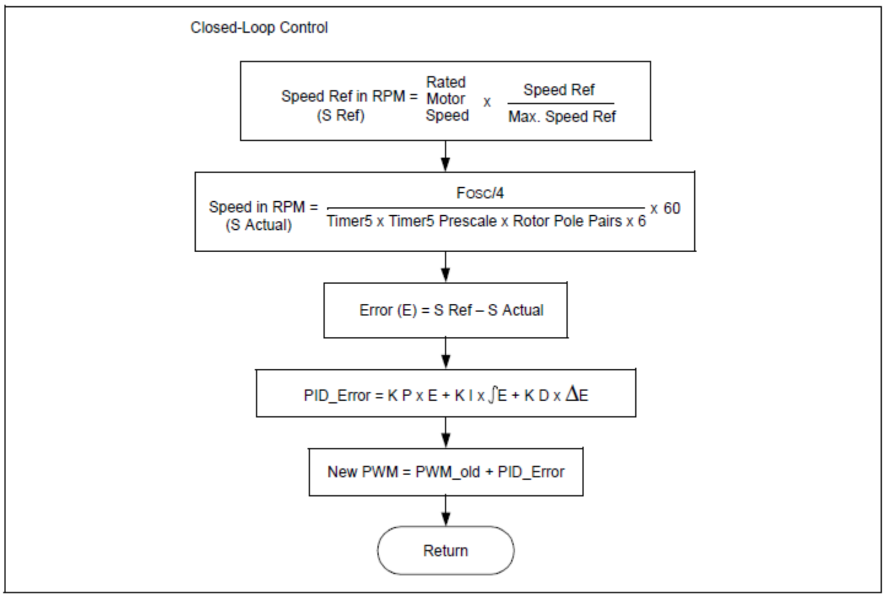


Figure 3.4: Speed error calculation using Hall sensor input

3.2.1.2. Using back-emf as input to determine rotor speed and position

Back-emf also can be used to determine the speed and also the rotor position. The angular velocity of the rotor can be determine by back-emf value because of the relation according to (1) which E is back-emf in voltage and ω is angular velocity in radian.

$$E = 2NlrB\omega \qquad (1)$$

Detecting calculating the back-emf is the main criteria in order for this control scheme to work. As the back-emf is the input to the microcontroller, determining specific position of the rotor using the back-emf is important.

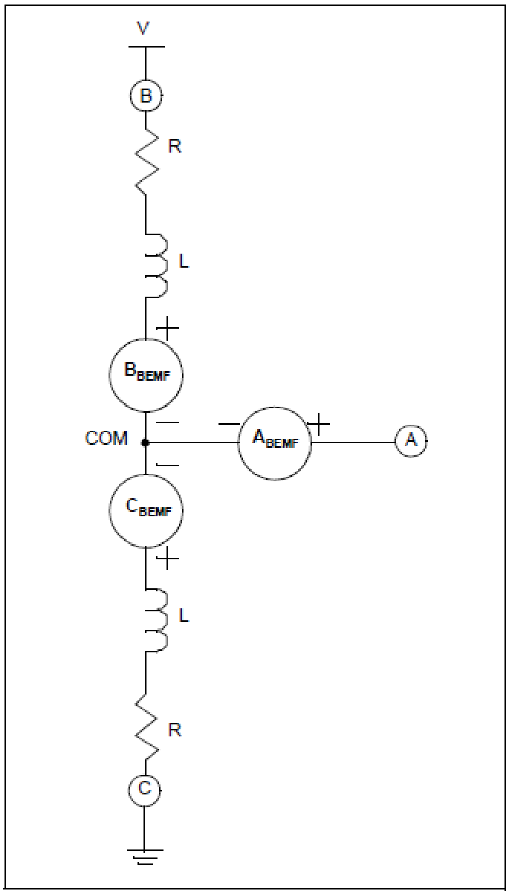


Figure 3.5: BLDC motor equivalent circuit

The back-emf, relative to the coil common point produced by coil A, B and C can be expressed as equation (2), (3) and (4).

$$B_{BEMF} = \sin(\alpha) \qquad (2)$$

$$C_{BEMF} = \sin(\alpha - \frac{2\pi}{3}) \qquad (3)$$

$$A_{BEMF} = \sin(\alpha - \frac{4\pi}{3}) \qquad (4)$$

Since the applied voltage used is Pulse Width Modulation (PWM), the drive alternates between on and off throughout the phase time. The back-emf, relative to ground, seen at the A terminal when the the drive is on, can be expressed as equation (5) and (6). Notice that, the winding resistance is cancel, so resistive voltage drop, due to motor torque load, is not a factor when measuring back-emf

$$BEMF_A = \frac{[V - B_{EMF} - C_{EMF}]R}{2R} - C_{EMF} + A_{EMF} \qquad (5)$$

$$BEMF_A = \frac{[V - B_{EMF} - C_{EMF}]}{2} - C_{EMF} + A_{EMF} \qquad (6)$$

The back-emf, relative to common connection, seen at terminal A also can be expressed as eqution (7).

$$BEMF_A = A_{BEMF} - B_{EMF} \qquad (7)$$

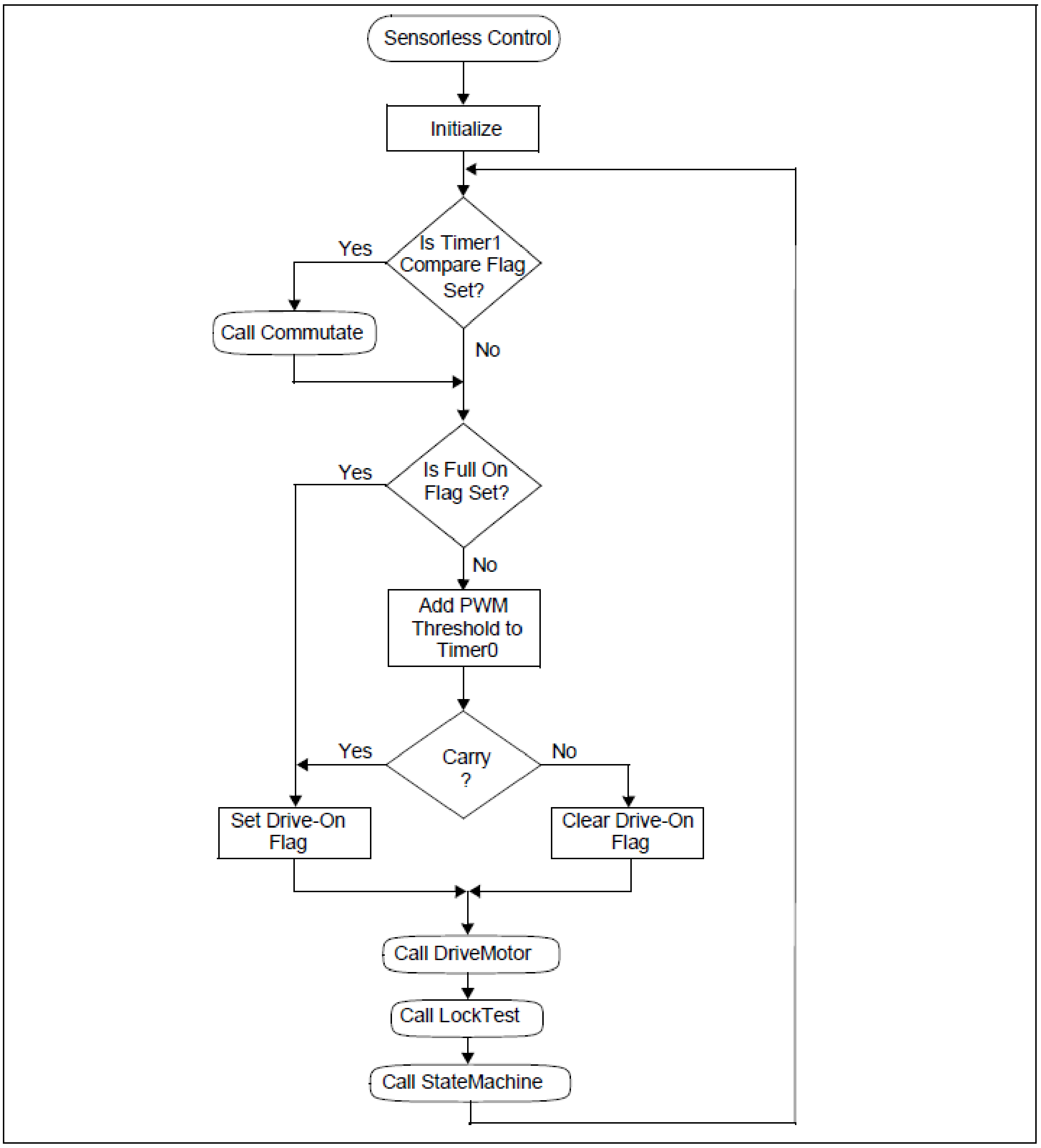


Figure 3.6: Sensorless control main loop

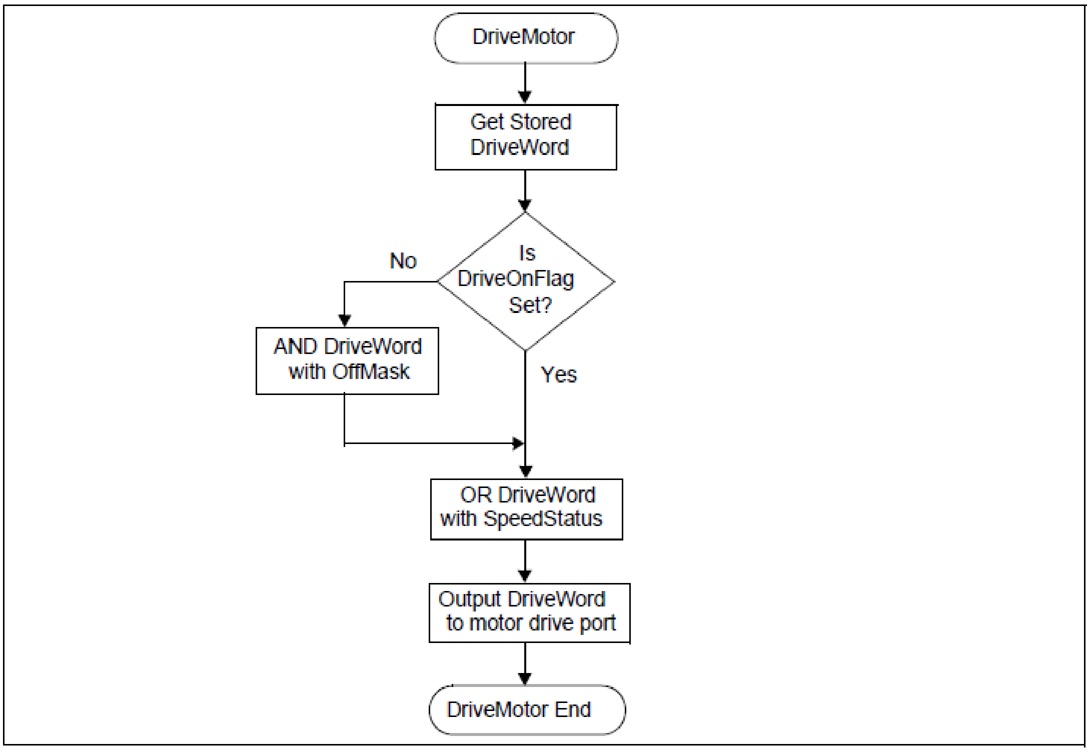


Figure 3.7: Drive motor control loop

3.2.1.3. Using Analog Hall Effect sensor to determine position

Due the characteristic of analog Hall Effect sensor, a single analog Hall Effect sensor can be to control the rotor position. The analog Hall Effect sensor will give analog DC input to the controller according to the rotor position. Microcontroller can use the input gain form the analog Hall Effect sensor to determine specific position of the rotor. For example, 3.4 V is equal to the 65° away from the reference position. So, specific position is known by using the analog Hall Effect sensor.

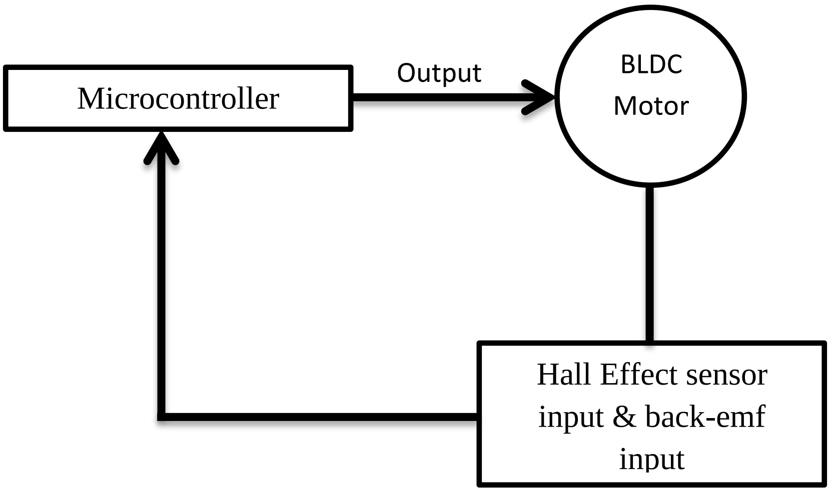


Figure 3.8: General control scheme for BLDC motor

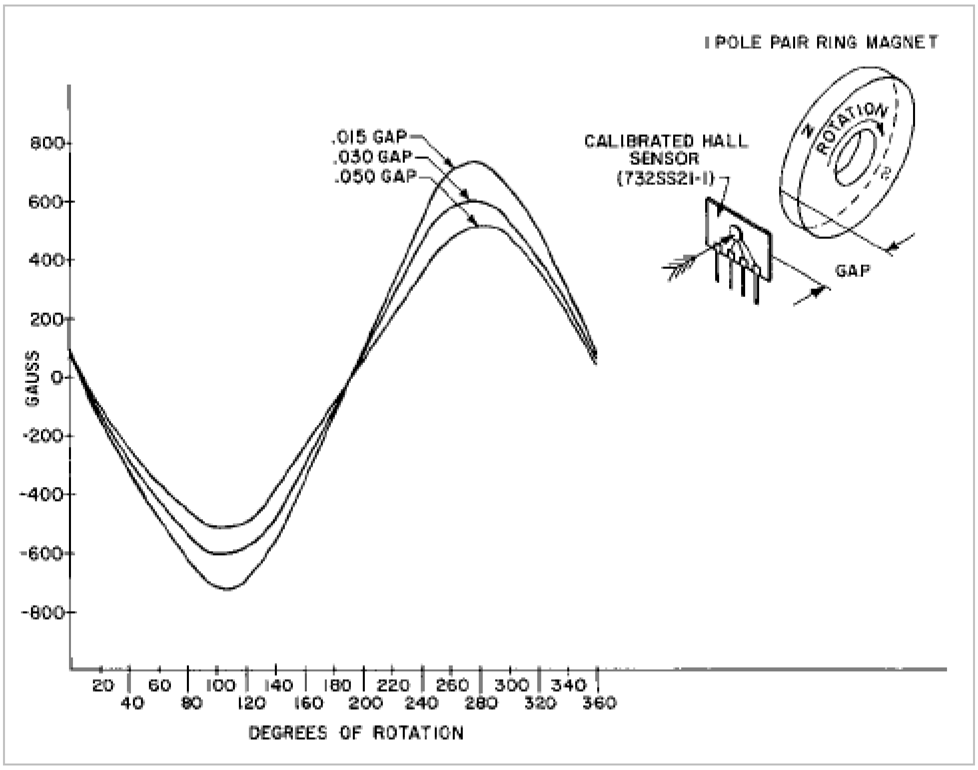


Figure 3.9: Magnetic field strength in Gauss level for rotational motion of ring magnet

3.2.2. Signal Measurement

For this project, to determine the exact position of the motor is important in order to achieve motor control. The hall sensor and back-emf output will be the input for the motor controller. Before using this signal as the input for the motor controller, the signal must be accurate, precise and also consistent to ensure reliability of the signal. In this part, the signal will be tested at certain consistent speed to understand the behavior of the signal produce by the motor.

3.2.2.1. Hall Effect Sensor Signal Measurement Procedure

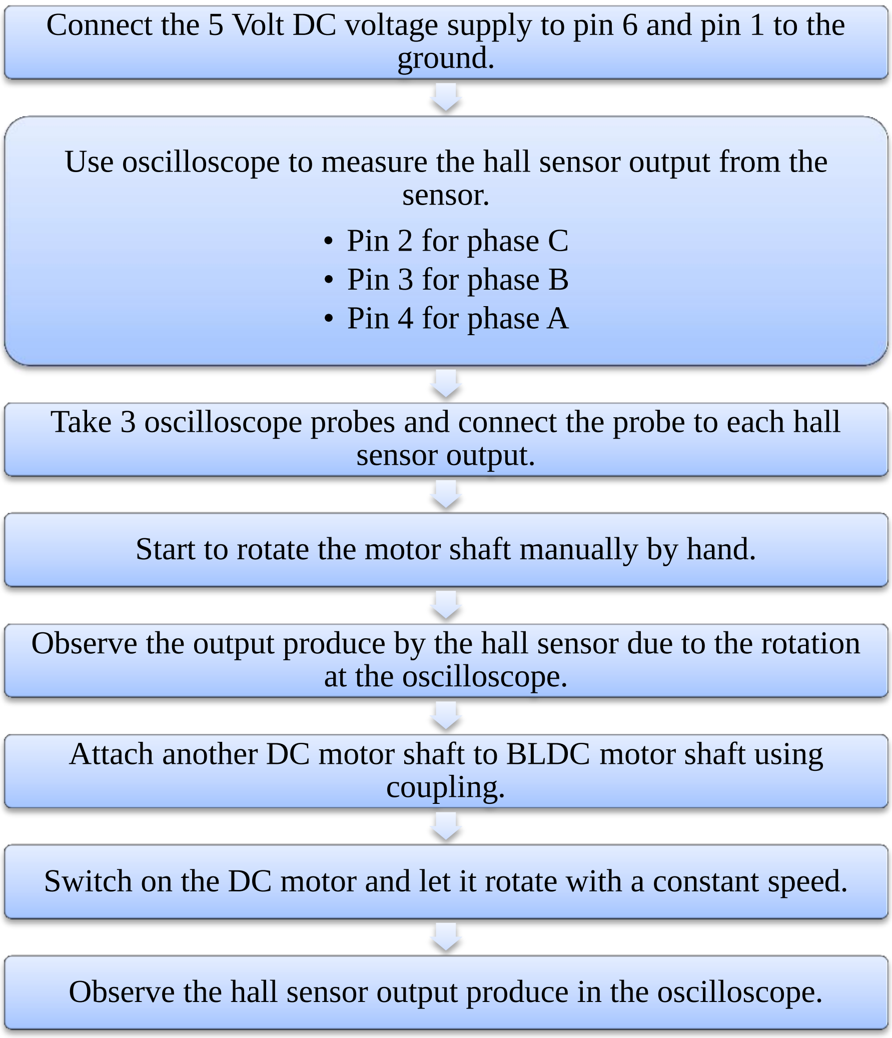


Figure 3.10: Hall Effect sensor measurement procedures

3.2.2.2. Back-EMF Signal Measurement Procedure

Take 3 oscilloscope probes and connect the probe to each motor phase.

↓

Connect the shaft of the BLDC motor and DC motor with coupling.

↓

Start to rotate the BLDC motor by implement voltage to the DC motor.

↓

Make sure the DC motor run at constant voltage.

↓

Observe the output produce by the back-emf due to the rotation at the oscilloscope.

↓

The step 5 and 6 is repeated with different speed and load to determine the unique characteristic of the BLDC back-emf.

Figure3.11: Back-emf signal measurement procedure

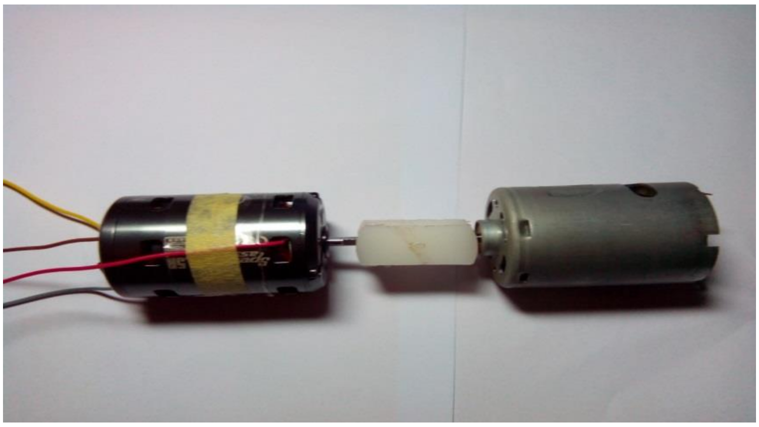


Figure 3.12: Connection of the BLDC and DC motor. For the BLDC motor wire, yellow (phase A), brown (phase B, grey (phase C) and red (common).

3.3. Strategy And Development Of The Algorithm

Last and the third part of the methodology are the strategy and development of the algorithm. Goal of this subsection is to develop the algorithm by divided the work into smaller tasks in order to have a better project flow. By divided the work into smaller task also will help to focus the objectives of this project.

For the position control programming algorithm, the tasks are distributed into smaller tasks. This make it easier for troubleshooting and avoid programming algorithm became messy with too much goals at one time. As for this project, the programming tasks are divided into several parts to achieve the main objective which is to achieve and demonstrate position control using BLDC motor.

3.3.1.1 Run DC Motor

This task is the most basic in this project programming part. In this assignment, the objective is to control DC motor with variable speed. Although this seem insignificant in this project, this assignment is very important because this algorithm will be use to drive the BLDC motor later in this project.

The DC motor will be drive using the microcontroller and the minimum and maximum speed of the DC motor will be observed. Also the DC motor will be use to drive the BLDC motor using the coupling. As the DC motor run the back-emf output of the BLDC motor will be observe. Then the back-emf value will be use as the input to implement position control of the DC motor. This is intent as experiment before proceed to use the BLDC motor for position control.

3.3.1.2 Read and Convert Bemf Signal

Back EMF will be the feedback input for the position control of this project. The back-emf will be connected to the analog I/O of the microcontroller. Then the signal will be computed so it can be used to determine the position of the BLDC motor.

Initially the back-emf will be used as input to run the DC motor. After that, the back-emf will be used to control the BLDC motor. In this programming algorithm, the objective is to manipulate the unique back-emf pattern of the BLDC. As there are 3 back-emf signals from each phase of the BLDC motor, these signals will supplement each other to determine the position of the rotor of the BLDC motor.

3.3.1.3 Run BLDC Motor Using Driver (Sensorless Control)

This is the next phase of the project. Driving the BLDC motor using the BLDC driver will give the idea and fundamental of the controlling BLDC motor. Above all, this task will give the knowledge to control the BLDC motor using the BLDC driver.

The driver is manipulating the Pulse Width Modulation (PWM) to control the speed of the BLDC motor. The microcontroller will give the signal towards the driver to control the BLDC motor. Later, the algorithm will be used for the next task.

3.3.1.4 Run Position Control in BLDC Motor using Bemf Signal as input

Position control for the BLDC motor will not be a direct method as the driver only capable of speed control. Nonetheless, the back-emf will be the input for the position control. This task is basically combining previous tasks to achieve the position control for the BLDC motor.

The 3 unique back-emf signals will be used to determine the BLDC motor position. In this task however, the accuracy of the position control might be not accurate but by achieving this task mean the position control of BLDC motor is viable. The position control algorithm later will be refining to achieve up to 5° angular rotation.

3.3.1.5 Implementing PID Control in the Position Control

Implementing the PID control in the position control is to achieve higher accuracy for the project. The PID control algorithm will be the compensator and will correct the error produced an accurate position control. The PID control is an essential to produce an accurate system.

The PID value need to be tuned before can be implement to the position control. The PID need to be optimized in order to avoid overshoot when implementing the position control of the BLDC motor. Besides the overshoot, the error also needs to be minimizing to avoid the accuracy of the BLDC motor deviated too much.

CHAPTER 4:

RESULTS AND DISCUSSION

4.1. Hardware Design And Justification

There are 3 important hardware in this project which is the BLDC motor, BLDC motor driver, and the microprocessor. Each hardware selection is based on the required specification to achieve the objectives of this project.

4.1.1. BLDC Motor Specification

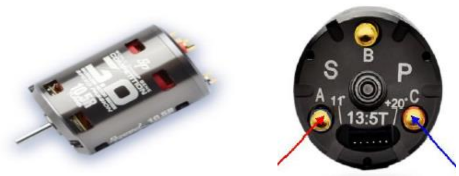


Figure 4.1: BLDC motor top view (left) and back view (right)

Voltage	12 V
Maximum Current	24 A
Internal Hall Sensor	Yes
Torque	50 mNm
Maximum Rotation	4000 RPM
Shaft Diameter	3.175 mm
Price	RM 190

Table 4.1: Motor Specifications

This motor is chosen because mainly this motor met all the requirements and specifications needed to complete this project. The motor voltage rating is 12 V and it is easy to find a driver with this specification. Besides that, the small size of this motor also a criteria why this motor is chosen. As the price is RM 190, it is by far cheaper than industrial grade motor.

4.1.2. BLDC Driver Specification

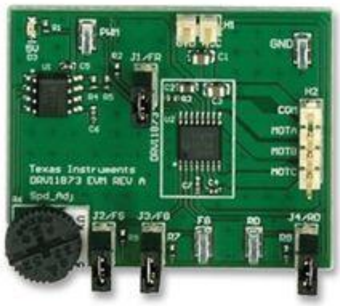


Figure 4.2: BLDC Motor driver

Voltage Supply	4V - 16 V
Maximum Current	1.5 A
PWM Input Range	15 kHz – 100 kHz
No. of MOSFET	6
No. of Motor Supported	1
Temperature Range	-40 ℃ to 125 ℃

Table 4.2: BLDC Motor Driver Specifications

This driver is chosen for this project because the operating voltage could supply the BLDC motor. With the range for 4V – 16V, the voltage range should be able drive the BLDC motor. The voltage range up to 16V means that the driver can support many range of motor. The PWM supported up to 100 kHz also means that the driver can be control using the PWM of the microcontroller. The driver is selected because of the low price. The price of the driver is about RM 100.

4.1.3. PICDEM PIC 18 Explorer Board Specification

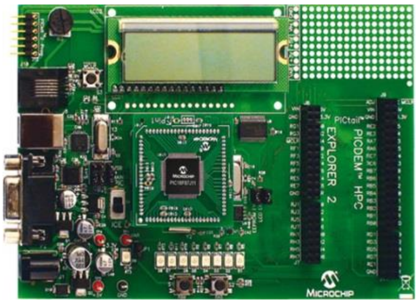


Figure 4.3: Microcontroller

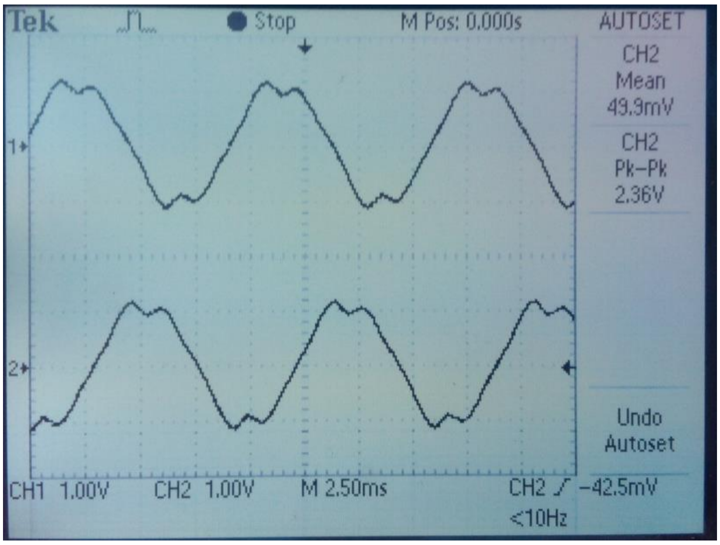
Microcontroller Unit	PIC 18 – 8 bit
A/D Converter	10 bits
Display	Alpha Numeric LCD
Voltage Supply	9 V – 12 V

Table 4.3: Microcontroller Specifications

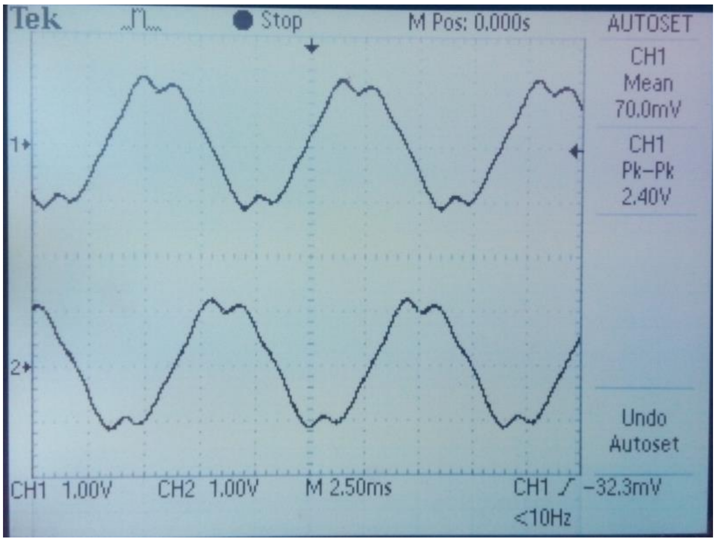
The microcontroller unit is selected for this project mainly flexibility using this platform. It can supported many format of programming including C/C++ and also assembly language. This microcontroller has been proven capable to do the sensored and sensorless commutation of the BLDC motor. Besides that, this microcontroller unit well establishes to execute PID control loop for many application such as driving BLDC motor used as cooling fan. The high number of I/O and A/D converter unit also the reason for this microcontroller is preferred. Extra feature like the LCD, 8-bit LED and internal variable resistor means that this microprocessor can be use stand alone to do many tasks without interface between external hardwares.

4.2. Back EMF Signal Measurement

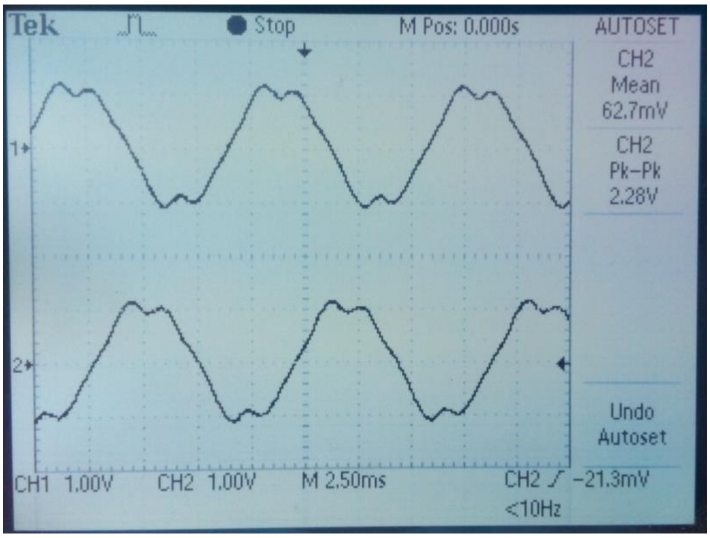
The back EMF characteristic of the BLDC will be important criteria to achieve and demonstrate position control of the BLDC motor. The back EMF is gain by coupling the shaft of the BLDC motor with a DC motor. Then, the DC motor is run with a constant speed to produce the back-emf.



(a)



(b)



(c)

Figure 4.4: BLDC back-emf output ;(a) phase a vs phase b back-emf; (b) phase b vs phase c back-emf; (c) phase c vs phase a back-emf

The back-emf produced is close to the theoretical trapezoidal waveform produce by BLDC motor. This back-emf is produced when the DC motor is drive at 5V and 3A. The peak-to-peak voltage produce is 2.6V. There is a ramp up and ramp down pattern as well as small sine wave in between of the ramp signal. The frequency of the waveforms is about 125 Hz. The phase A and phase B waveform is about 120° out of phase with each other's. This unique waveform can be used to determine the position of the BLDC motor. The ramp signal will be used as the input to control the position.

As 3 phase of waveform is produced by the BLDC motor, combining the waveform can produced a good measurement platform to determine the position of the BLDC motor. The back EMF produced also consistent and have very small variation mean that the signal is reliable to be used.

4.3. Position Control Of BLDC Motor Using Back-EMF

Position control using back-emf had never been done before this. A good indicator of position control is the accuracy of the angular rotational accuracy. Initially in the methodology, a 5° accuracy is aim to be achieve in this project. However, at this moment the position control only able to achieve up to 10° - 15° accuracy and the position control is done using DC motor driven by the back-emf of the BLDC that coupled together. An independent BLDC positon control has not been achieve due to the mixture of PWM signal of the motor driver with the back-emf of the BLDC motor.

Although at this moment only DC motor driven by the BLDC back-emf can be achieved, it is possible to have position control using only BLDC motor. With only 10° - 15° accuracy is achieved, the project is capable to reach up to 5° accuracy. In order to achieve higher accuracy for this back-emf based control, a signal filtering method is needed. This is because the signal produce by the motor driver is in PWM signal and interrupt the back-emf signal. This produce a mixture of signal and clean back-emf signal need to be attain in order to achieve higher accuracy. The signal filtering is two pronged approach to obtain clean back-emf for control and allow the BLDC motor to do position control independently.

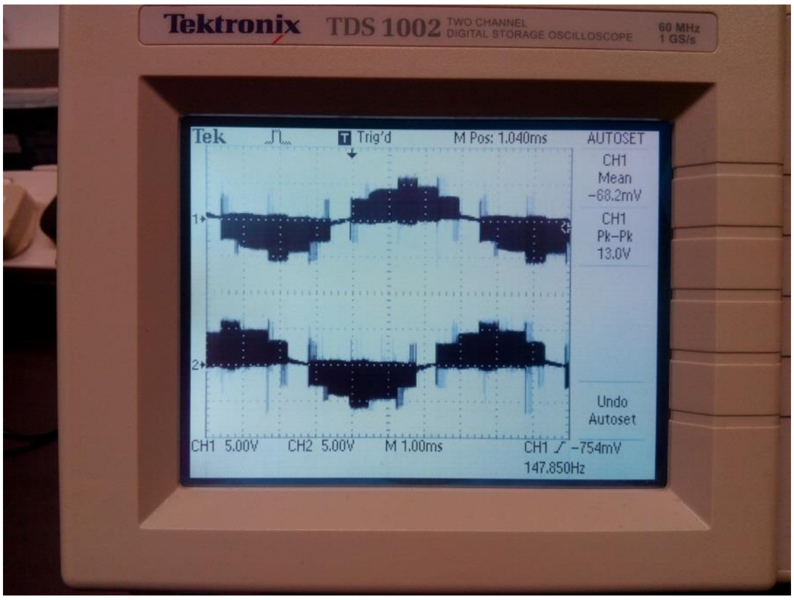


Figure 4.5: Back-emf signal mixture with motor driver PWM signal

The challenge in the future is to filter the mixture of driver PWM signal and back-emf signal and to get a clean back-emf signal without the PWM signal from the driver. A filter need to be design and tested to obtain an optimum filter that can isolate the back-emf signal.

4.4. Project Key Milestones

No	Project Activities			Status	
1	Project Literature			Ongoing	
2	Draft Control Scheme			Ongoing	
3	Determine Hardware Specification	1	BLDC Motor	Ongoing	
		2	Motor Controller	Ongoing	
		3	Microprocessor	Ongoing	
4	Hardware Purchasing	4	BLDC Motor	Ongoing	
		5	Motor Controller	Ongoing	
		6	Microprocessor	Ongoing	
5	Data Measurement	7	Back-Emf Output	Ongoing	
6	Design Control Scheme and Algorithm			Ongoing	
7	Test and Fine Tune The Control Algorithm			Ongoing	
8	Design and Implement Projects Deliverables			Ongoing	

Table 4.4: Key Milestones completed (Green)

CHAPTER 5:

CONCLUSION AND RECOMMENDATION

The BLDC position control is possible but at this stage it only can be shown when driving a DC motor using BLDC back-emf. The filter needs to be design in order to accomplish the objectives that is to demonstrate the position control of the BLDC motor using back-emf. With DC motor coupled with the BLDC motor combination the accuracy of the angular rotational is 10° - 15°. The initial 5° accuracy can be achieve if a clean back-emf can be ontained.

Although at this stage the BLDC motor position control cannot be demonstrate, with a proper and optimum signal filtering method, these project objectives can be obtained.

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