3-PHASE BRUSHLESS PERMANENT-MAGNET MOTOR CONTROL FOR HYBRID ELECTRIC VEHICLE IN-WHEEL MOTOR

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By

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Dissertation submitted in partial fulfillment of
the requirements for the Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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JUNE 2010

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 references and acknowledgements and that the original works contained herein have not been undertaken or done by unspecified sources or persons.

(Mohd Farizol Fuzmi Bin Mohd Bakhi)

ABSTRACT

This report discusses the project done by the author on the proposed topic, which is **3-Phase Brushless Permanent-Magnet Motor Control for Hybrid Electric Vehicle In-Wheel Motor.** The project is about applying a 3-phase brushless in-wheel motor (IWM) to drive the rear wheels of a conventional vehicle based on the hybrid electric vehicle technology. The hybrid electric vehicle achieves better fuel economy than a conventional vehicle. This report present the study on characteristics of BLDC motor, the control of in-wheel motor for hybrid electric vehicle and the behavior of an additional control strategy which is speed control – in addition to torque control that exists in most motor controllers. Data and results are obtained from field experiments on the motor model. A brushless DC motor uses electronic commutation for basic operation. Thus, the motor controller or brushless motor drive system will do the commutation to operate the brushless motor and the wheels of the car will also rotate. The challenge in this project is to understand functionality of the motor controller to control the BLDC and to configure program an external controller for speed control of the IWM.

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LIST OF ABBREVIATIONS

DC	Direct Current
BLDC	Brushless Direct Current
EMF	Electromotive Force
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
EMS	Energy Management System
EMC	Energy Management Controller
NI	National Instruments
IWM	In-wheel Motor
ABS	Air Back System
LCD	Liquid Crystal Display
UTP	University Technology PETRONAS

CHAPTER 1
INTRODUCTION

1.1 Background of study

Brushless DC motor (BLDC) is one of the popular types of motor used in applications such as appliances, automotive, aerospace, consumer, medical, industrial automation equipment and instrumentation [2]. In a BLDC motor, the permanent magnet will rotate while the armature (stator winding) remains stationary. The commutator is replaced with intelligent electronic controller that will do the electronic commutation.

In contrast, in a brushed DC motor, the brushes make mechanical contact with the rotor part called commutator, forming an electrical contact with the armature coil-windings. BLDC motors have many advantages compared to brushed DC motors, for example, more compact construction, better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation and high speed ranges. Figure 1 below shows the cross section of a BLDC motor [1].

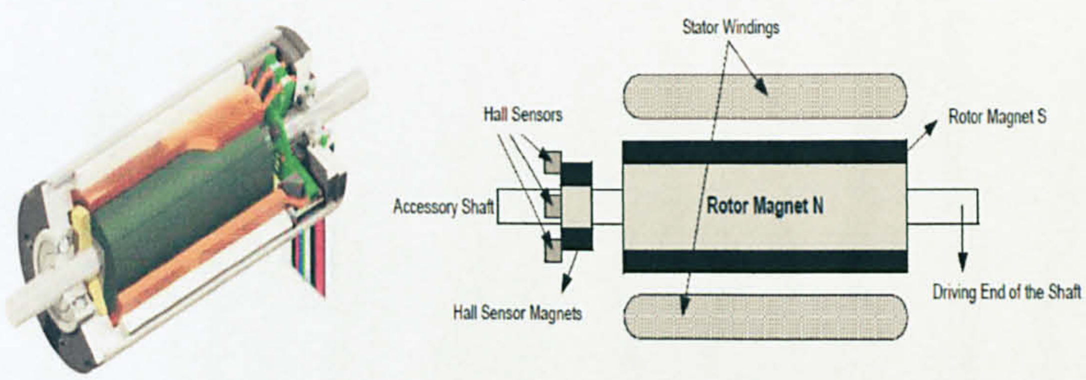


Figure 1: Brushless Direct Current Motor (BLDC)

As shown in Figure 1, a brushless DC motor usually consists of three main parts: stator, rotor and Hall sensors.

1.1.1 Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery as shown in Figure 2. The stator of a BLDC is constructed the same as an induction motor type. But, only the windings of the stator for both types are distributed in a different manner. In this project, the BLDC motor used has three stator windings connected in wye-connection. Each of the winding is constructed of conductor coils interconnected to form a winding. These windings are distributed over the stator periphery. The different interconnection types of stator winding result in either a trapezoidal or sinusoidal motor, which gives different types of electromotive force (EMF) [2].

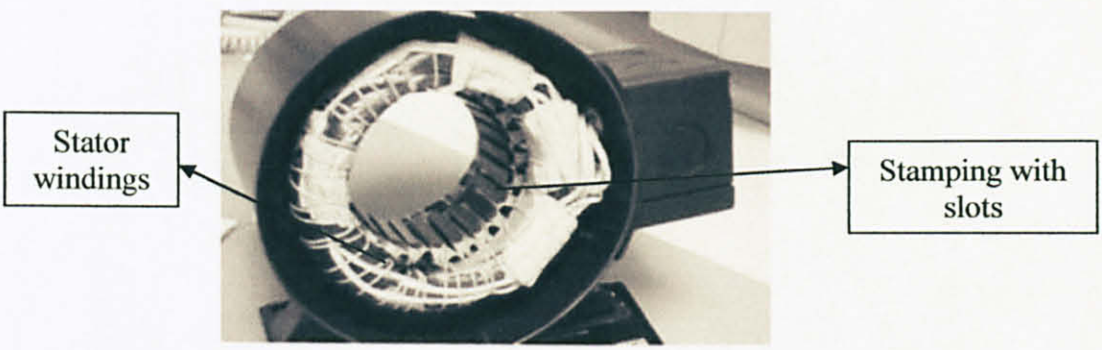


Figure 2: Stator of BLDC

1.1.2 Rotor

The rotor holds the permanent magnets. It consists of an even number of permanent magnets and can vary from two up until eight pole-pairs with alternating North (N) and South (S) arrangement. The coils are stationary while the magnets are rotating. Referring to the magnetic field density required in the rotor, the proper magnet is chosen to make the rotor. Usually ferrite magnets are used. As technology advances, rare-earth alloy magnets become more popular. The ferrite magnets are less expensive but have low flux density. Compared to the alloy material which has high a magnetic density per volume and enable a smaller rotor for the same torque. It also improves the size-to-weight ratio and gives higher torque. Examples of rare-earth alloy magnets are Samarium Cobalt (SmCo), Neodymium (Nd), Ferrite and Boron (NdFeB) and etc [2]. Figure 3 shows the rotor cross-section in a BLDC motor [3].

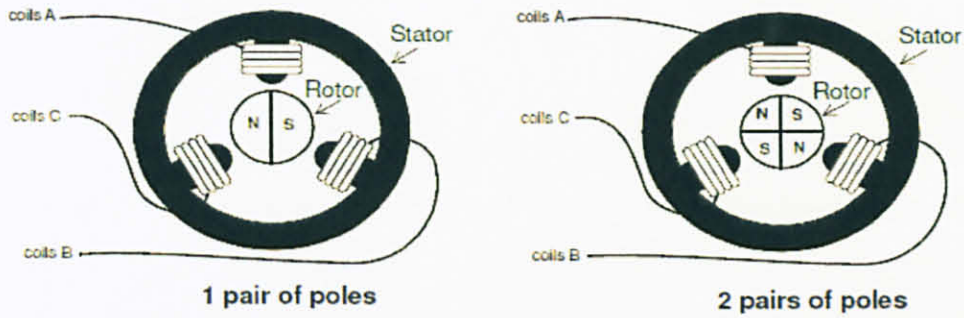


Figure 3: Rotor cross-section in a BLDC motor

1.1.3 Hall Sensors

The rotor position is sensed using hall effect sensors that are embedded into the stator placed at the non-driving end of the motor. They give a high or low 5V-signal, indicating North or South pole of magnet when the rotor pass near the Hall sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined [2]. Figure 1 shows the placement of the hall effect sensors [1].

E. H. Hall (1879) explains the hall effect: "If an electric current carrying conductor is kept in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers which tends to push them to one side of the conductor. This is most evident in a thin flat conductor. A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor." [2]

1.2 Problem Statement

A brushless motor (BLDC) is also called a synchronous motor powered by direct current. The brushless DC motor uses electronic commutation to operate, so a motor controller or brushless motor drive system is needed to do the commutation process. There are two methods of controlling a BLDC motor, namely sensor and sensorless control. In this project, the sensor method is used to control the BLDC motor. A 3-phase BLDC motor drive system includes MOSFETs or Insulated Gate Bipolar Transistor (IGBTs). IGBTs are capable of operating higher voltage and current compared to MOSFETs. This project is to study basic and implement BLDC operation an additional control strategy, which is speed control – in addition to torque control that exists in most motor controllers. The application of the BLDC motor is in-wheel motor in a hybrid electric vehicle. A prototype model of in-wheel BLDC motor is being constructed at UTP and this prototype will be used for testing of the speed control. The author will implement the speed control using external hardware and software - *National Instruments' Compact RIO* hardware and *LabVIEW* software.

1.3 Objectives

The objectives of this project are listed below:

- To study different types of motor controllers for brushless motor and understand the functions
- To configure and perform brushless motor control using off-the-shelf motor controllers
- To familiarize with the characteristics of BLDC motor by field experimentation
- To implement speed control using external hardware and software (*National Instruments' Compact RIO* hardware and *LabVIEW* software)

1.4 Scope of Study

The study will be in two stages, where the first stage involves installing the necessary hardware including studying and performing wiring and connections between the brushless DC motor and the controller. The second stage involves field experimentation and testing. This hardware configuration is very important in order to do research and experiment to familiarize with the characteristics of BLDC motor, followed by the study of speed control of the motor. This project also involves study and do research on different types of motor controllers and also different types of brushless motors. This project aims to understand PWM switching which is responsible for electronic commutation and speed control to drive the brushless motor. Configuration and implementation of the experimental set-up of the working model to get the results for analysis will also be performed. Speed control will be studied and implemented using external hardware and software.

CHAPTER 2
LITERATURE REVIEW

2.1 Theory

Basically, there are two methods of controlling the BLDC which are sensor and sensorless. Sensorless operation uses some kind of back electromotive force (EMF) as feedback signal while sensor operation uses Hall effect sensors as feedback position sensors to commutate the brushless motors. Every brushless DC (BLDC) motor requires a drive and controller to supply commutated current to the motor windings synchronized to the rotor position. Figure 4 below shows the drive system for a BLDC motor [4]. BLDC motors can come in single-phase or 3-phase configurations. Out of these, 3-phase brushless motors are the most popular and widely used.

There are different types of drive that can be used: unipolar or bipolar drive, constant or variable bus voltage operation and open or closed loop drive. There are different objectives that can be achieved from these different types of drive. Some drives are just commutating while others may include voltage control with or without closed-loop current control. In this project, a closed-loop drive is used to control the BLDC motor. In order to control the speed of motor, a closed-loop drive can be applied where required speed is compared with the measured actual speed and the motor is driven using speed error signal. Because the motor's speed is roughly proportional to the terminal voltage of the BLDC motor, variable speed operation is possible by changing the terminal voltage, which is achieved by varying the duty cycle of the PWM [4].

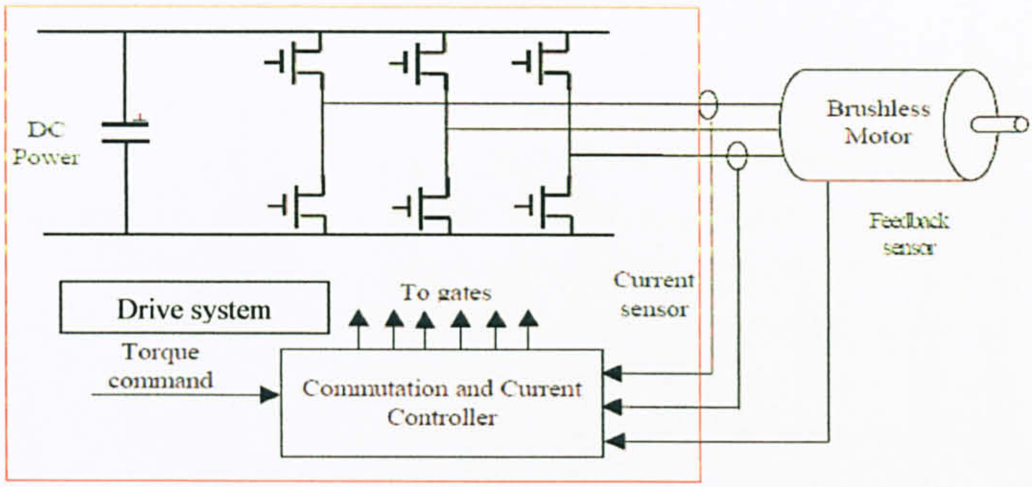


Figure 4: Block diagram of BLDC motor drive

2.2 Operation and Control

For three-phase brushless DC motor application, the most common topology used is three-phase inverter bridge. The typical drive system which used on this project is as shown in Figure 4 [4]. The output stage consists of a 3-phase inverter composed of 6 transistor switches that could be either MOSFETs or IGBTs. The BLDC drive requires variable frequency, variable amplitude excitation that is provided by the 3-phase inverter bridge.

Feedback is needed from position sensor of the BLDC motor to switch on and off the six inverter switches - S1 to S6. PWM signal is used to control the switches gate. Pulse Width Modulation (PWM) technique is used to regulate the actual currents to the rectangular current reference waveform [5]. In this project, the speed control circuit is designed to operate with PWM. Therefore, the average applied voltage across the motor stator windings can be controlled by modulating the duty cycle of the PWM signal to the inverter bridge.

2.3 Electronic Commutation

Commutation is the process of switching current into the phases (coils) of BLDC motor to result in or rotation of the motor. If a common BLDC motor is used in producing a force, the windings must be switched in polarity and amplitude relative to the permanent magnet's fields. In a BLDC motor, the permanent magnet are on the moving shaft or rotating part while in a brushed motor, the magnets are usually static which known as stator part. In general, there are various different schemes of electronic commutation. For example: six-step, sinusoidal and trapezoidal (square) commutation [4].

2.3.1 Six-Step Commutation Method

The six-step commutation method is the simplest method compared to the other methods of commutation. Six-step commutation looks more like the trapezoidal commutation method. Figure 5 below show each phase voltage is positive (negative) when top switch is ON (OFF) and bottom switch is OFF (ON). Each phase voltage is activated for 120° (electrical degree). No voltage is injected when both switches are OFF, where in this case the actual terminal voltage is governed by the back EMF voltage of motor. Each phase voltage at a time takes one of three states which are positive, negative and floats. In order to commutate properly, at every 60° degree only one phase is energized positive and one of the other is energized negative in order to maintain current path [4].

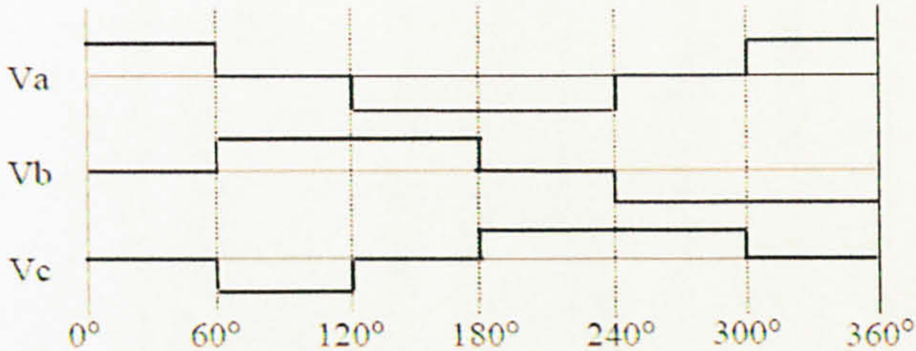


Figure 5: Six-step commutation phase voltages

2.3.2 *Trapezoidal Commutation Method*

Trapezoidal commutation consists of applying current to only two of the three windings at a time. Thus, only two of the six inverter switches are conducting at any time, and only two of the three windings carry current at any time. During one commutation interval, current is injected into one motor lead, returning through a second lead and the third lead is open. As the rotor rotates, different windings are energized, sequencing through six possible combinations through one electrical revolution. Figure 6 shows the trapezoidal or square mode commutation [6].

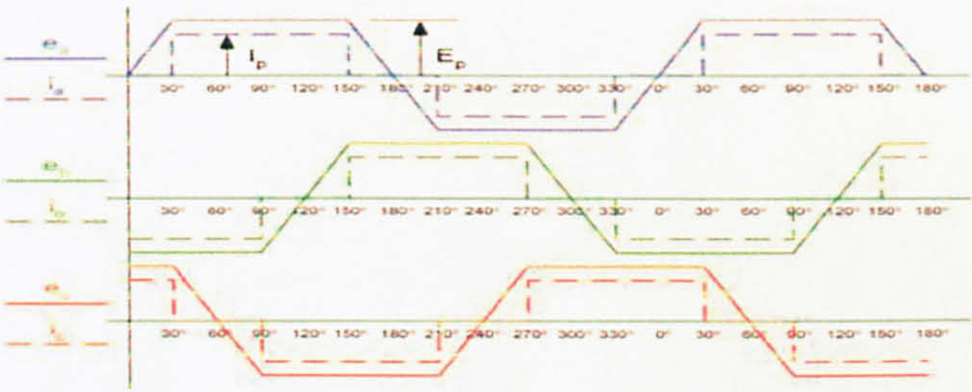


Figure 6: Trapezoidal or square waveform

2.3.3 *Sinusoidal Commutation Method*

In contrast, for sinusoidal commutation each of the three phases of the inverter is modulating (PWM) all the time, driving 3 out-of-phase sinusoidal currents into each winding. It can be done by two methods: the first one is rectangular commutation using digital Hall sensor which generate pulses as the motor passes over magnetic poles of magnet. The other method is by using a sinusoidal encoder. Figure 7 shows the sinusoidal wave [6]. The advantages of sinusoidal commutation is it can delivers absolutely smooth torque at any rotational angle or speed and thus a small torque ripple (assuming that back EMF is close to sinusoidal), quieter operation and efficiency compared to trapezoidal 6-step commutation method [4].

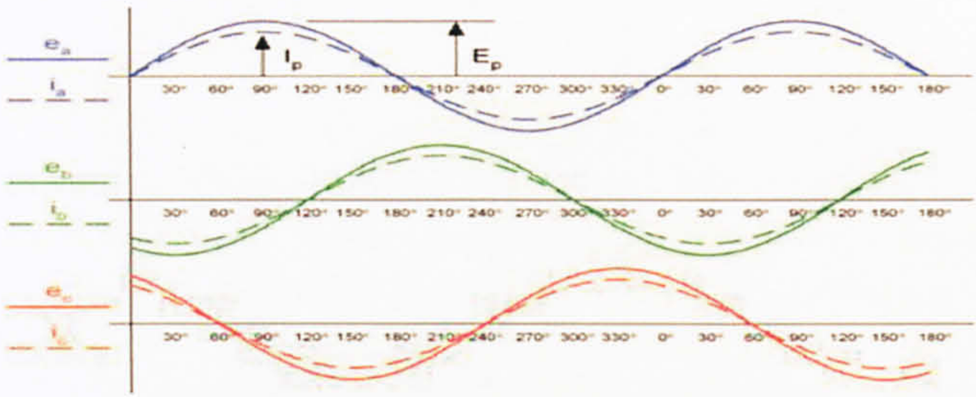


Figure 7: Sinusoidal waveform

2.4 Motor Controller

There are many motor controllers that can be used for the project. The motor controller is used to control and monitor the BLDC motor. Figure 8 shows the type of motor controller that will be used for the working model of the in-wheel motor (smaller version). This motor controller is integrated with the MOSFET transistor switching inside. So, it does not need an external MOSFET or IGBT drive to operate the brushless motor.

For the working model, the 4-Q PWM servo, SCA-B4-70-30 type motor controller, from Electrocraft Company, will be used to drive the BLDC motor. Figure 8 shows the 4-Q PWM servo motor controller. It requires a single DC power supply for operation. It has the functionality of speed control that will be studied in this project. It is protected against under-voltage, short circuits, over-current, and over-temperature. It has multiple modes of operation: torque and speed control [7].

Figure 8: 4-Q PWM servo motor controller

2.5 Speed Control

In a speed controller, the motor's speed (or velocity) is being controlled. There is an element that detects speed, either tachometer or some sort of encoder or hall sensor. This monitoring element provides the feedback to the speed controller to either increase or decrease speed. The speed controller controls the speed of the motor by increasing or decreasing the applied voltage to the motor.

Commutation ensures proper rotor rotation of the BLDC motor, while the motor speed depends on the applied voltage. The applied voltage is adjusted by varying duty cycle of PWM. As voltage is applied, there is a resulting current flowing through the motor winding. This current provides torque to spin the motor. This current is not being controlled directly, but through applied voltage. A speed controller can control speed in either a clockwise direction or a counterclockwise direction by applying a positive or negative voltage.

For this project, the speed controller is implemented as a conventional PI controller. The difference between the actual and required speed is input to the PI controller and, based on this difference, the PI controller controls the duty cycle of PWM pulses, which corresponds to the voltage amplitude required to keep the required speed. Figure below show the speed controller for brushless motor [8].

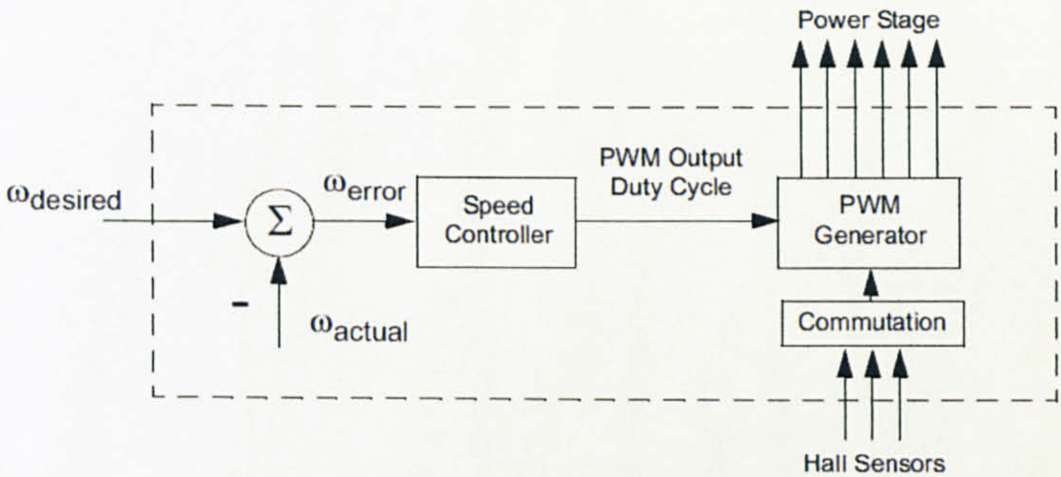


Figure 9: Speed controller

The speed controller calculates a Proportional-Integral (PI) algorithm according to the following equations [8]:

$$u(t) = K_{c\left[e(t)+\frac{1}{T_1}\int_0^t e(\tau)d\tau\right]}$$

Transformation to a discrete time domain using an integral approximation by a Backward Euler method yields the following equations for the numerical PI controller calculation [8]:

$$u(k) = u_P(k) + u_I(k)$$

$$u_P(k) = K_c . e(k)$$

$$u_I(k) = u_I(k-1) + K_c \frac{T}{T_1} . e(k)$$

where:

e(k) = Input error in step *k*

u(k) = Controller output in step *k*

$u_P(k)$ = Proportional output portion in step *k*

$u_I(k)$ = Integral output portion in step *k*

$u_I(k-1)$= Integral output portion in step *k-1*

T_1 = Integral time constant

T = Sampling time

K_c = Controller gain

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

In order to achieve the objectives of the project, some research is done on some resources from books, jurnals and technical papers to obtain information that related to complete this project. A lot of steps or methods need to be followed to accomplish the project successfully. At the early stage of the project basically study and research on how the brushless motor it operated with the controller, the characteristics of brushless motor and controller, and configure the connection of hardware.

After all the equipements or work model has been setup, testing and experimenting will be conducted to obtain the expected results for studied. Then, implement the speed control program that used to control the speed of brushless motor. Refer to the Gantt Chart (APPENDIX A) to see the schedule of work progress. Procedures involved for the project design development are shown in Figure 10.

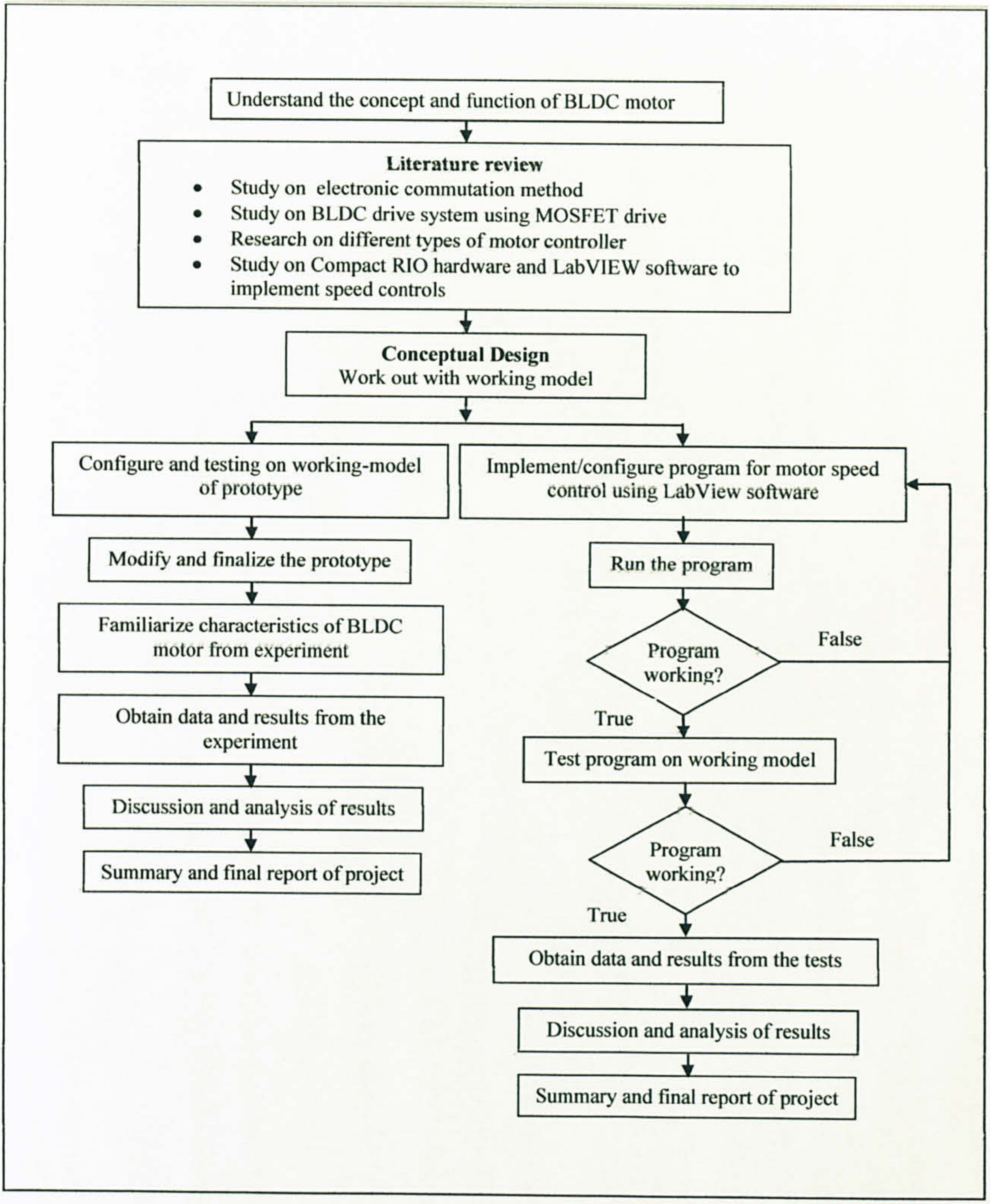


Figure 10: Flow Chart of Project

3.2 Tools and Equipments Required

Below are the expected tools and equipments needed for completion of the project. These equipments are obtainable at UTP. The software required is also available. The equipments are:

- 3-phase BLDC Motor (prototype)
- Integrated MOSFET drive and controller - from *Electrocraft*
- LabVIEW 8.5 Software
- NI Compact RIO (external motor speed controller)
- RC lowpass filter (connecting *Electrocraft* 's input and *CompactRIO* 's output)
- Oscilloscope
- Function generator

RESULTS AND DISCUSSION

4.1 System Block Diagram

Figure 11 below shows the early concept for the overall project titled 3-Phase Brushless Permanent-Magnet Motor Control for Hybrid Electric Vehicle In-Wheel Motor.

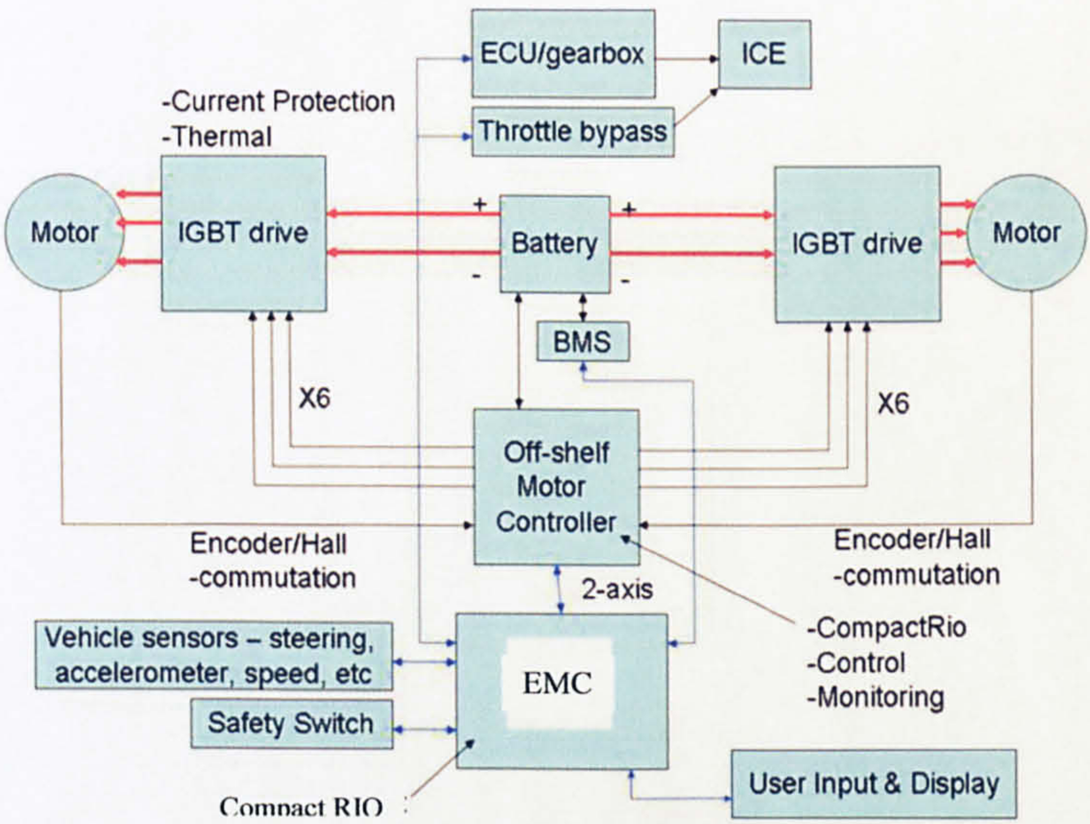


Figure 11: System Block Diagram of In-Wheel Motor Project for Hybrid Electric Vehicle

In the initial plan of the project, it is proposed to have a separate controller for Energy Management System (EMS) and motor controls. The main reason for this idea is because the motor controller for IGBT drive would require higher rate frequency more than (>2 kHz) for pulse width modulation (PWM) signal while the controller for EMS requires lower control rates. Motor controller will control the two IGBT drive for the IWMs based on control input send by the EMS. Main control output is the PWM switching signals for the IGBT drives and the main input is the commutation signal from the IWMs send by EMS.

IWM stands for In-Wheel Motor. Both the rear left and right wheels of the vehicle are fitted with IWMs (the wheels are attached with the brushless motor). In an electric vehicle that has in-wheel motors in its driving wheels, each wheel's motor torque can be controlled independently. The results of different torque between left and right wheels are also possible to generate [10].

EMS will control the operating modes of the system and will interface with user inputs like throttle, brake, mode selector, display LCD panel and etc, data from ECU/gearbox on engine operating points and also fuel level, battery management system, vehicle sensors for example steering angle, accelerometer, speed, ABS signal and etc, and safety switch that will include internal and external manual safety switches.

4.2 Block Diagram of Brushless Motor Drive System

The first block diagram below (Figure 12) shows, the basic elements of brushless motor drive: 3-phase brushless motor, DC bus supply, motor controller embedded with MOSFET inside (Electrocraft), speed detector (tachometer) and position sensor (Hall sensor). The second block diagram (Figure 13) shows the speed control system. This block diagram can be divided into two phases:

4.2.1 Overall Brushless Motor Drive System

Figure 12 below shows the working model of BLDC motor drive. The objectives are to study the characteristics and the behavior of controlling BLDC motor. In the first phase, to configure the connection and wiring between the BLDC motor and off-the-shelf motor controllers. Follow with by perform BLDC motor control using off-the-shelf motor controller. The study is done by constructing several tests and experiments in order to familiarize with the characteristics of the BLDC motor. However, this motor controller cannot be used to support and control the actual BLDC motors fitted in the rear wheels of the car, because of the low power capacity of the Electrocraft controller. In the car, a much higher power capacity (voltage and current) motor controller is used.

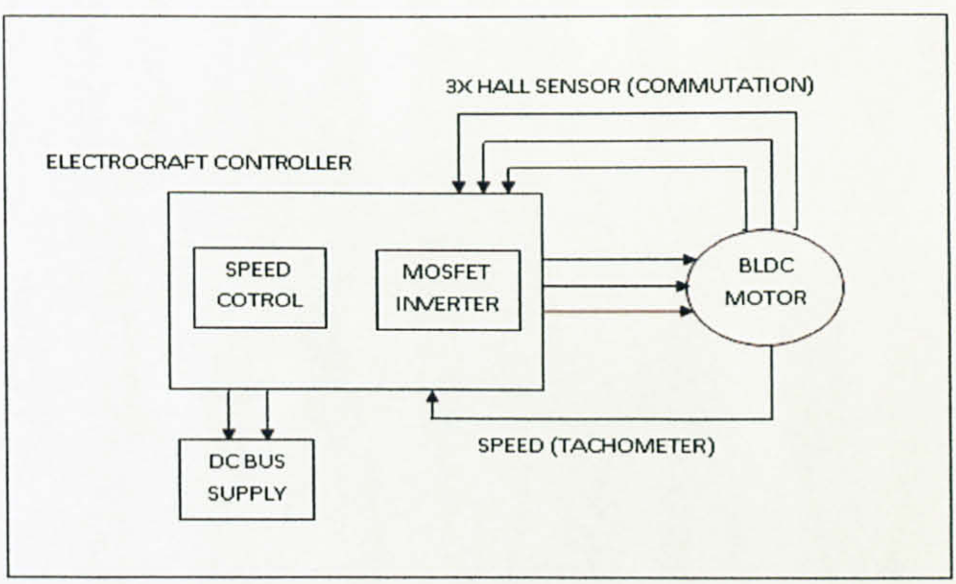


Figure 12: Overall brushless motor drive system

4.2.2 Block Diagram of Motor Speed Control

Figure 13 below shows the block diagram of motor speed control. The second phase is to implement speed control using external hardware and software. For this speed control, the program will be implemented using LabVIEW software and will be downloaded to the Compact RIO controller that is connected to BLDC motor. The speed of the motor is directly proportional to the applied voltage. Using Pulse Width Modulation (PWM) by switching the transistors on and off that embedded inside the Electrocraft controller, a varying average voltage can be applied to the BLDC motor. When both the high side and low side transistors are ON for 100% of the commutation period, the motor will run at the rated speed provided the rated dc voltage is supplied. For operating the motor at a desired speed below the rated speed, the commutation pattern applied at either high side or low side should be pulse-width-modulated (PWM).

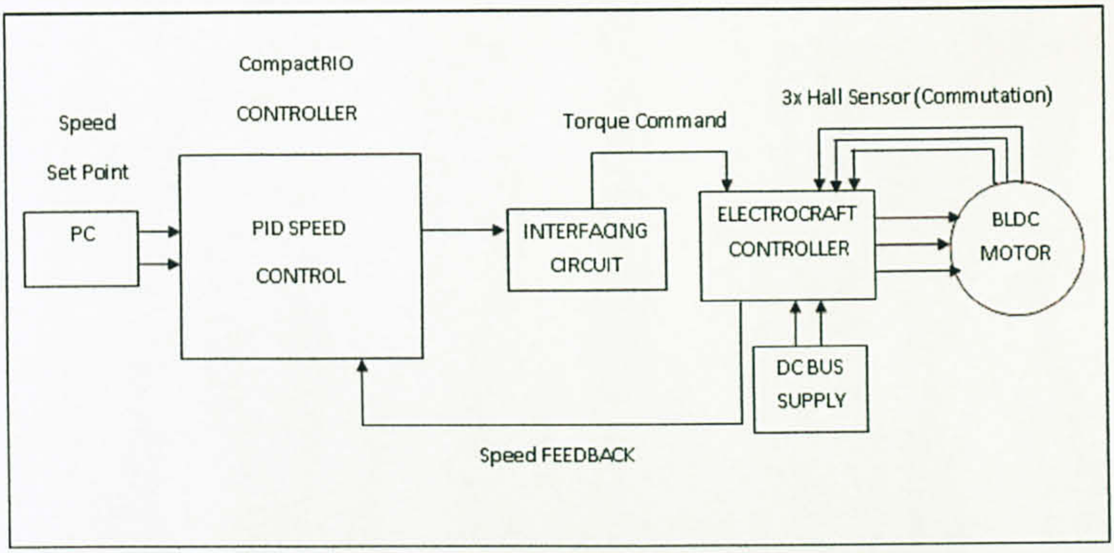


Figure 13: Block diagram of motor speed control

4.3 Experimental Studies and Results

Experiments are conducted in the Automotive Research Centre Laboratory using the 3-Phase BLDC Control for working model. This working model of the in-wheel BLDC motor is constructed in-house. Configuration and performing brushless motor control using off-the-shelf motor controllers and all experiments are conducted to characterize and familiarize with the characteristics of brushless DC motor. Specifications of the brushless motor are included in the Appendix.

4.3.1 Analysis of 3-Phase Back-EMF Waveform of BLDC Motor

The objective of this experiment is to make sure the constructed BLDC motor produces the required back-EMF waveform compared to the theoretical expectation. The waveform obtained will be compared with the theoretical waveform. This experiment is conducted by connecting the oscilloscope with the in-wheel BLDC motor by using probes. The probes are connected to phase A, phase B and phase C of in-wheel BLDC motor to the oscilloscope. Figure 14 below shows the connections of the brushless motor and the oscilloscope.

Figure 14: Brushless motor and oscilloscope

The experiment is conducted several times. This is important to obtain more accurate and consistent results. In order to generate the 3-phase back-EMF sinusoidal waveform, the brushless motor must be rotated. Then, the 3-phase back-EMF waveform will appear on the oscilloscope screen. Figure 15 below shows the waveform captured by the oscilloscope.

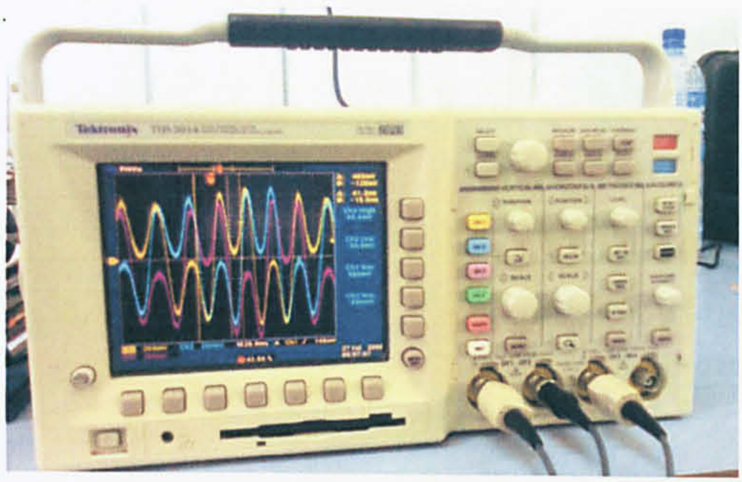
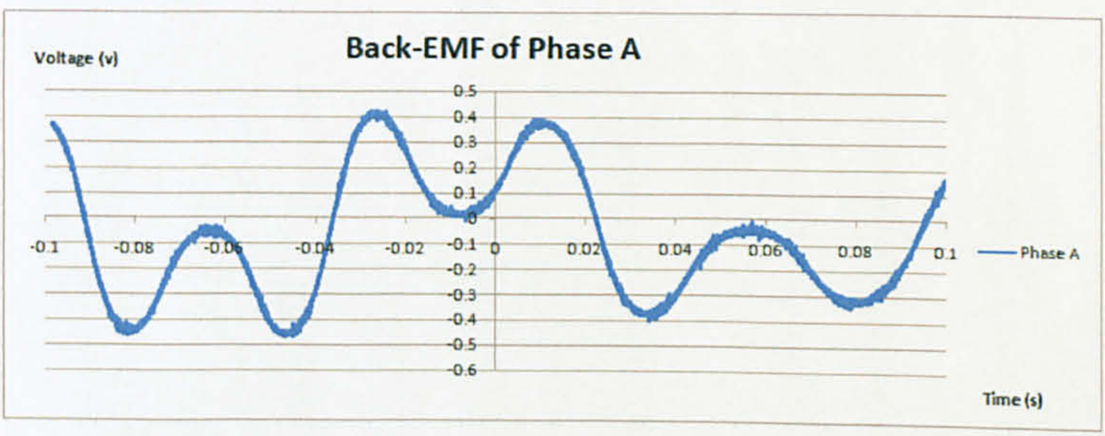


Figure 15: Back-EMF waveform of BLDC motor

Data from the oscilloscope is saved and transferred to Microsoft Excel for analysis. There are 10000 data points collected to produce the waveform. Using Microsoft Excel, the 3-phase back-EMF waveform is regenerated. Figure 16 shows the 3-phase back-EMF graph obtained from the Microsoft Excel.



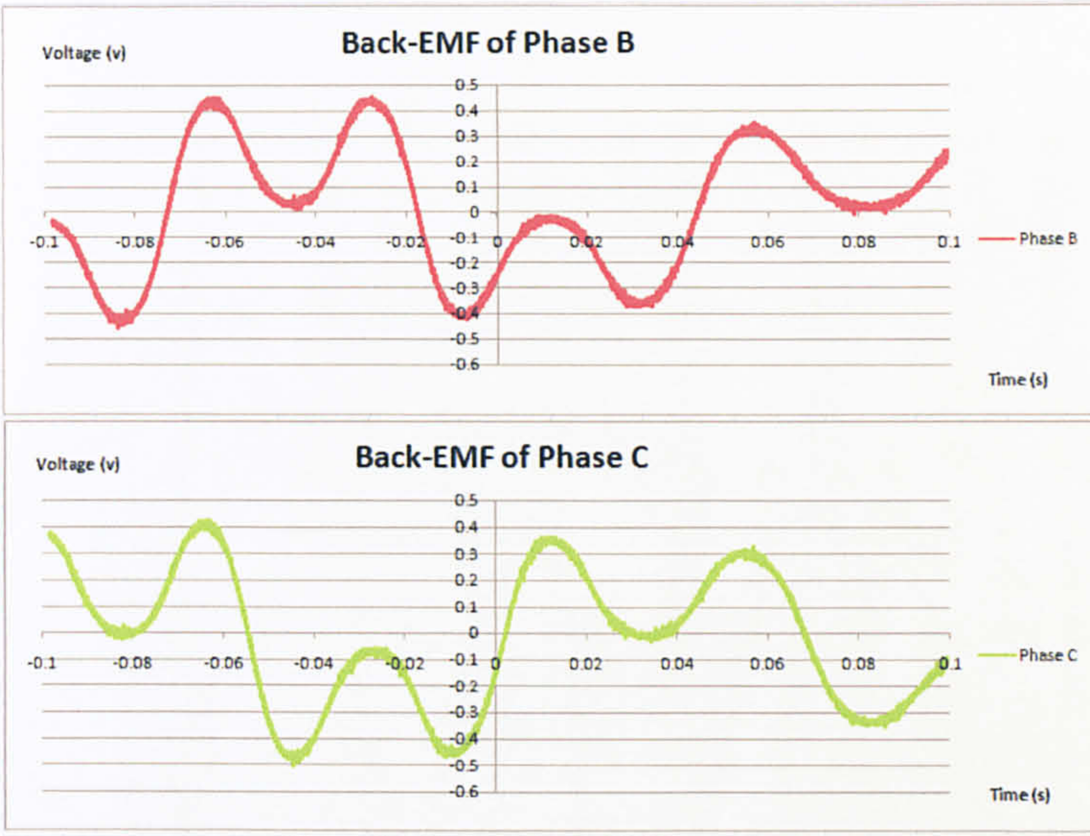


Figure 16: 3-phase Back-EMF waveform

The waveform of 3-phase back-EMF is compared with the expected waveform (Figure 17). But, the waveform showed on oscilloscope and generated by Microsoft Excel does not look like the expected 3-phase back-EMF waveform. This is due to design construction and fabrication defect of the BLDC motor itself.

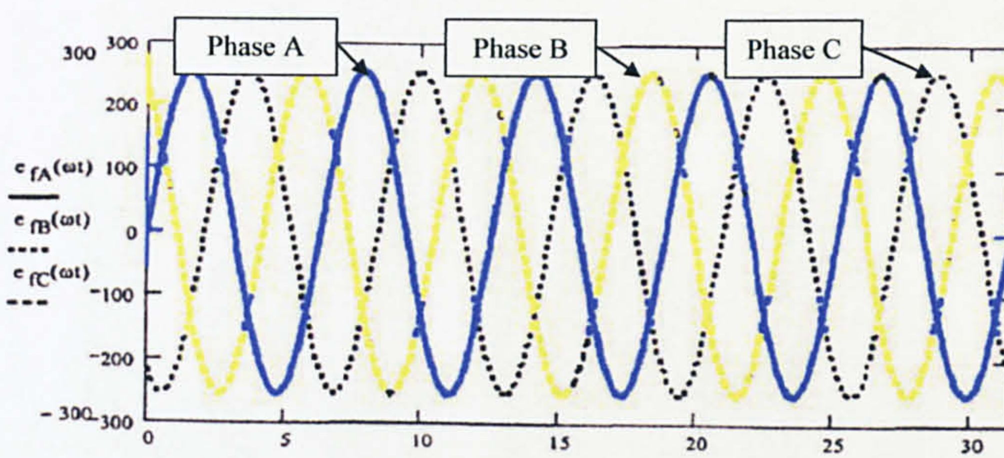


Figure 17: Expected 3-phase Back-EMF waveform [11]

After redesign and reconstruction of the brushless motor, the same experiment is repeated to obtain the waveform of 3-phase back-EMF. The new waveforms obtained are compared with the theory (Figure 17). Figure 18 below shows the 3-phase back-EMF graph obtained from the Microsoft Excel.

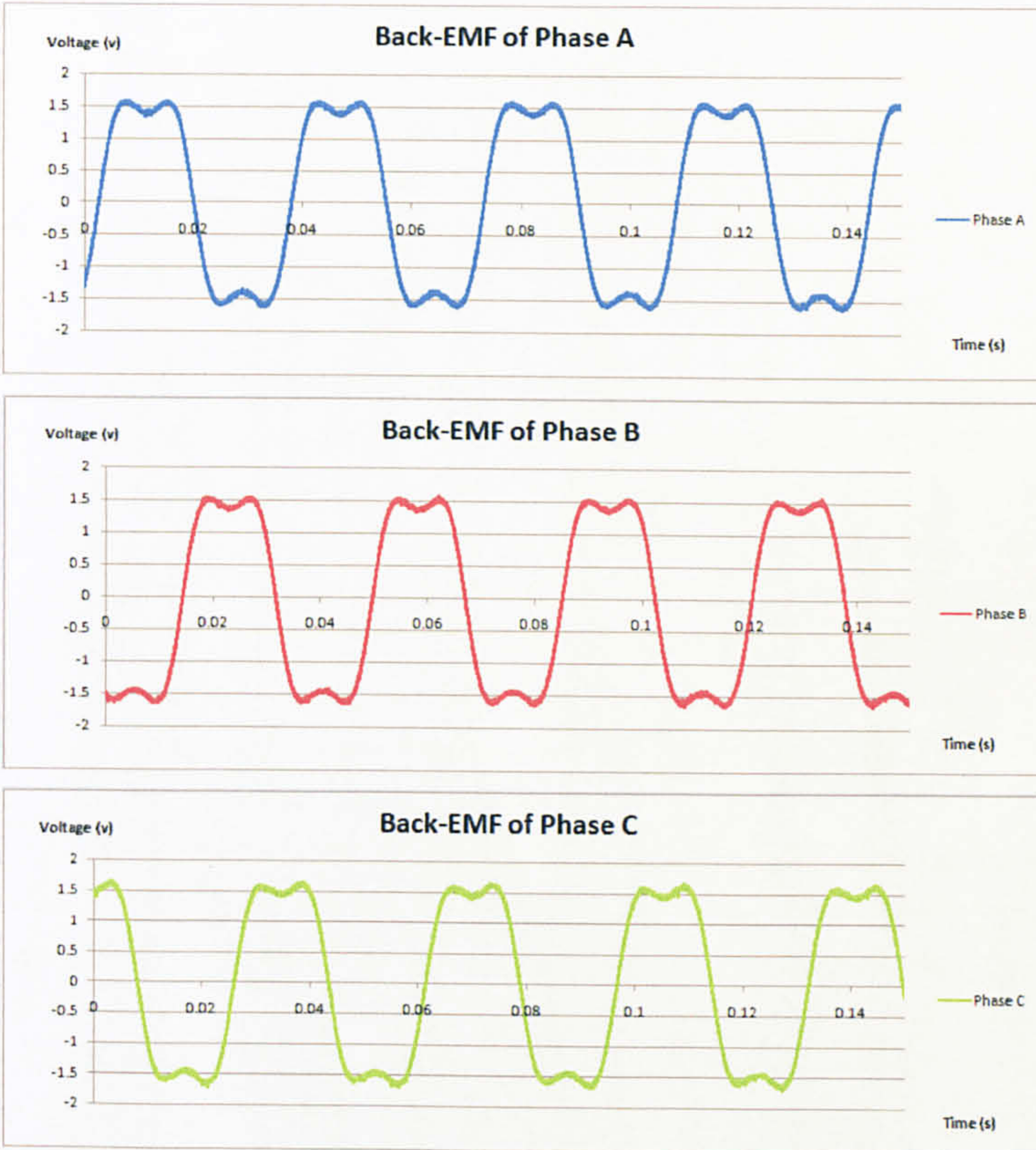


Figure 18: 3-phase Back-EMF waveform

From Figure 18, the waveform of 3-phase back EMF is more similar to the theoretical one, compared to the first set of graphs.

4.3.2 Analysis the Position of Hall Sensors

In brushed motors, the commutator itself switches the armature windings in order to provide the magnetic flux and armature current to interact with each other and to make the motor move. But for brushless motors, Hall sensors sense the position of the rotating magnet and excite the proper winding through send the logic (0-5V) signal to the controller. The output signal from this Hall sensor is very important for controller to do the commutation and as a feedback input for control the speed of BLDC motor. The rotor or permanent magnet is rotated moving across the front of the Hall sensors causes it to change state.

For this project's BLDC motor, the Hall sensors are placed 30 degrees apart from each other. When each north pole permanent magnet passes the Hall sensors, these Hall sensor will detect. These Hall sensors only detect the north part of the permanent magnet rotor of the BLDC. It must be supplied with 5 V to make the Hall sensor operate. The Hall sensors used is of the normally open-collector output type. It sends the output signal 0V (OFF) to -5V (ON) to the controller. But, the Electrocraft controller itself only accepts the input signal 0 to +5V. The signal needs to be inverted from 0 to -5V to 0 to +5V in order to be accepted by the controller.

This problem is solved by using an external pull-up resistor (Figure 19) that is connected between the Hall sensors output to the controller. The Hall sensors are embedded to the plate and fixed near the rotor magnets of the brushless motor. This enables adjustment of the Hall sensors to align with the rotor magnets to achieve better performance during the experiment. Misalignment of these Hall sensors, with respect to the rotor magnet will affect the output of position sensors and the commutation process itself.

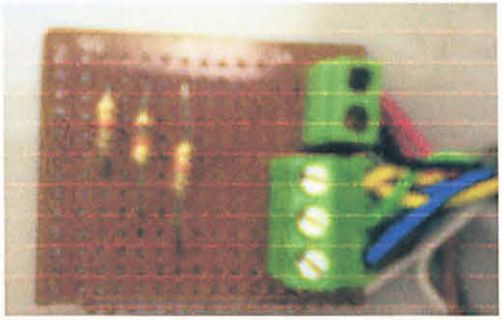


Figure 19: External pull-up resistor

The experiment is conducted by taking the three Hall sensors output when the brushless motor is rotating and compared to the expected Hall sensors output signal. Figure 20 below shows the output signal of the Hall sensors for Hall A, B and C obtained from the oscilloscope and regenerated using Microsoft Excel. The signals are then compared with theory (Figure 21).

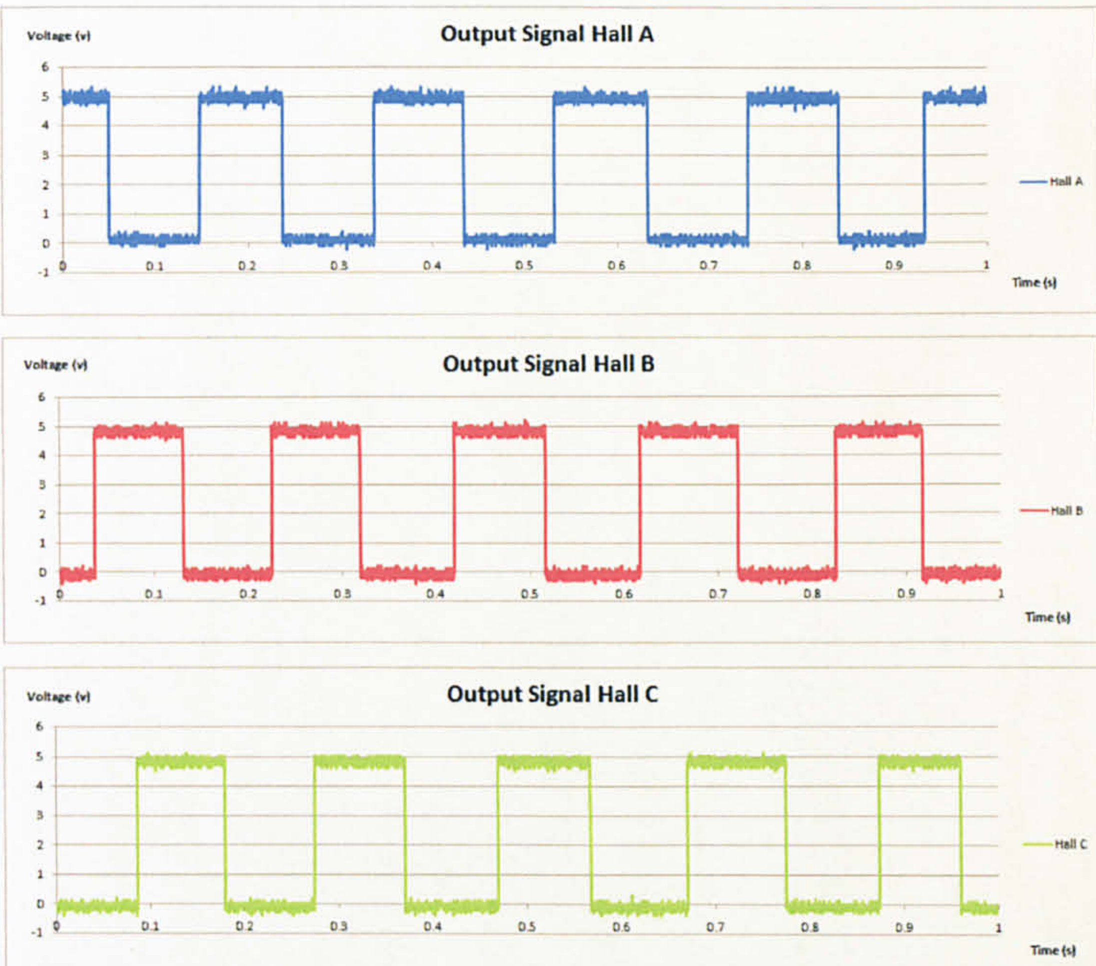


Figure 20: Output of Hall sensor A, B and C

Figure 21: Expected output of Hall sensor A, B and C [12]

After comparing Figure 20 with 21, both graphs of output signal are seen to be almost the same. But, a little bit difference due to the position of Hall sensor that detect the north of permanent magnet and also the construction of stator coil of brushless motor itself. But, the brushless motor can rotate as usual even though the output signals Hall sensors sent to controller are completely not accurate.

4.3.3 Calculate Speed of One Rotation of BLDC Motor from Hall Sensor

In the brushless motor drive, speed or velocity signals are essentially required for speed control loops in position controlled and speed controlled drives. Speed measurement can be either using speed transducers/sensors or estimated using the rotor position information either obtained through direct position sensing or through estimation. The speed of the brushless motor is measured by using output of Hall sensor signal. The Electrocraft controller itself determines the speed of BLDC motor from the output Hall sensor. This is a closed-loop speed mode which is using the Hall signals as a feedback input for the speed. The experiment below shows how to calculate the speed one rotation of brushless motor by using output signal of Hall sensor.

Procedures:

1. Set up equipment for experiment whereby BLDC motor will act as a generator: induction motor will rotate the BLDC motor with constant speed as shown in Figure 22 below.
2. Setting speed of induction motor by 15 Hz on inverter of induction motor.
3. Measure the speed of BLDC motor rotate by induction motor by using tachometer in order to compare with the calculation make from Hall sensor signal waveform.
4. Take single sequence of Hall sensor (Hall sensor A) waveform.
5. Calculate the speed of one rotation of BLDC motor.
6. Compare with the speed from tachometer.
7. Take data multiple times for accuracy and validation of speed measurement.

Figure 22: Set-up BLDC motor as Generator

(a) Test 1:

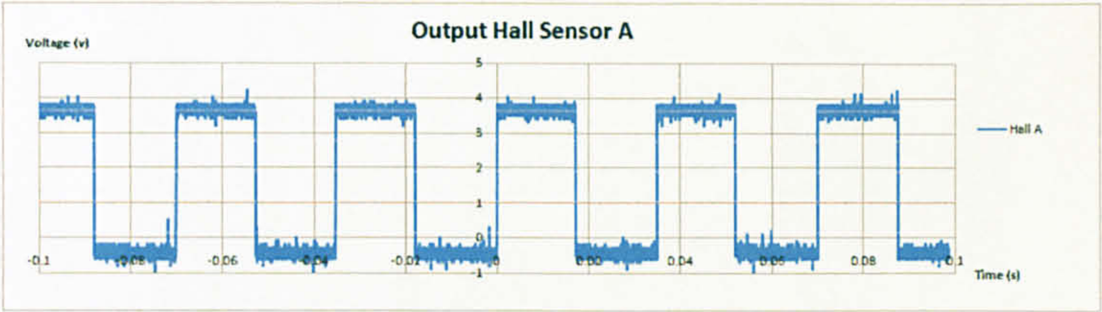


Figure 23: Output of Hall sensor A

Time of one cycle = time of one division X num. division per cycle

$$= 20 \text{ ms } \times 7$$

$$= 140 \text{ ms}$$

$$\text{Frequency (Hz)} \quad = \frac{1}{t}$$

$$= \frac{1}{140 \text{ ms}}$$

$$= 7.142 \text{ Hz}$$

Speed (rpm) $= \text{frequency (Hz)} \times 60 \text{ second}$

$= 7.142 \text{ Hz} \times 60 \text{ second}$

$= 428.57 \text{ rpm}$

(b) Test 2:

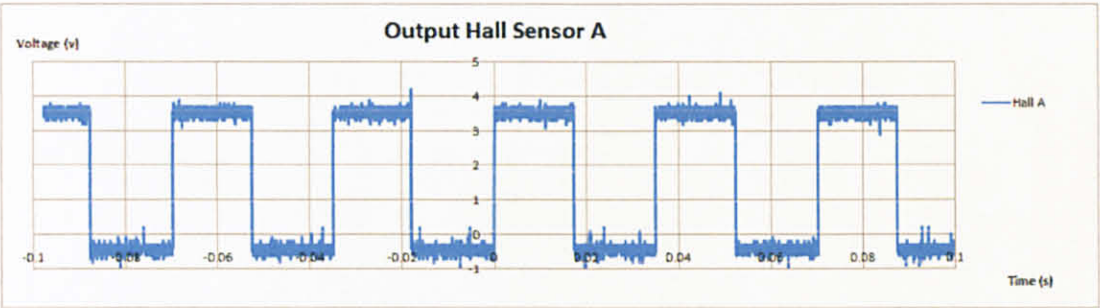


Figure 24: Output of Hall sensor A

Time of one cycle $=$ time of one division X num. division per cycle

$= 20 \text{ ms} \times 7$

$= 140 \text{ ms}$

Frequency (Hz) $= \frac{1}{t}$

$= \frac{1}{140 \text{ ms}}$

$= 7.142 \text{ Hz}$

Speed (rpm) $= \text{frequency (Hz)} \times 60 \text{ second}$

$= 7.142 \text{ Hz} \times 60 \text{ second}$

$= 428.57 \text{ rpm}$

(c) Test 3:

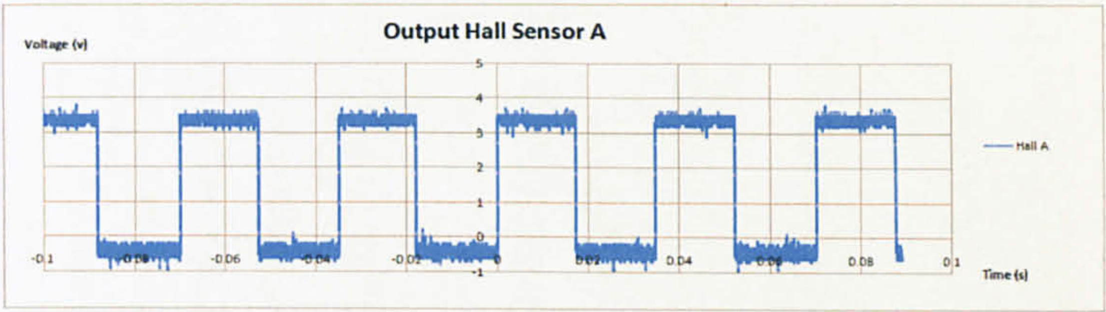


Figure 25: Output of Hall sensor A

$$\text{Time of one cycle} = \text{time of one division X num. division per cycle}$$
$$= 20 \text{ ms } \times 7$$
$$= 140 \text{ ms}$$

$$\text{Frequency (Hz)} = \frac{1}{t}$$
$$= \frac{1}{140 \text{ ms}}$$
$$= 7.142 \text{ Hz}$$

$$\text{Speed (rpm)} = \text{frequency (Hz)} \times 60 \text{ second}$$
$$= 7.142 \text{ Hz } \times 60 \text{ second}$$
$$= 428.57 \text{ rpm}$$

Get the average speed from this calculation:

$$\text{Average speed} = \frac{428.57 + 428.57 + 428.57}{3}$$
$$= 428.57 \text{ rpm}$$

Then, compare the calculation with the speed measure by tachometer:

Tachometer = 428.3 rpm

Calculation = 428.57 rpm

As the conclusion, the speed can be inferred (measured and calculated) by using the output signal of the Hall sensors. From this, speed control can be implemented using the Hall sensors for speed measurement.

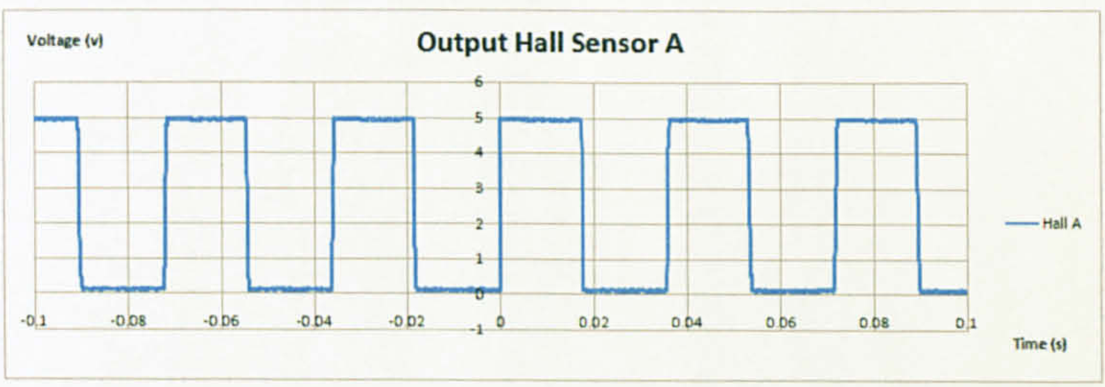
4.3.4 Calculate Back-EMF Constant (per phase), K_V.

The back-EMF constant, K_V can be calculated by getting speed of the brushless motor in one rotation and voltage phase. The speed of brushless motor in one rotation can be calculated from output signal of Hall sensor. For this case, Hall A will be the used to calculate the speed, and the back-EMF of phase A waveform will be used to measure the voltage. The experiment is conducted more than once to get an average value and for accuracy.

Procedure:

1. Set up equipment for experiment-BLDC motor will act as generator-induction motor will rotate the BLDC motor with constant speed
2. Connect the probes oscilloscope to the Hall A and coil A(phase A)
3. Setting speed of induction motor by 15 Hz on inverter of induction motor
4. Take single sequence of Hall sensor and back EMF (Hall sensor A) waveform
5. Calculate the speed of one rotation of motor from output of Hall sensor
6. Measure the voltage from the back EMF sinusoidal waveform
7. Calculate the back EMF constant, K_V from the value obtained
8. Repeat this procedure with different speed to get average value of K_V, for example 20 HZ, 25 Hz.

(a) Test 1: 15 Hz



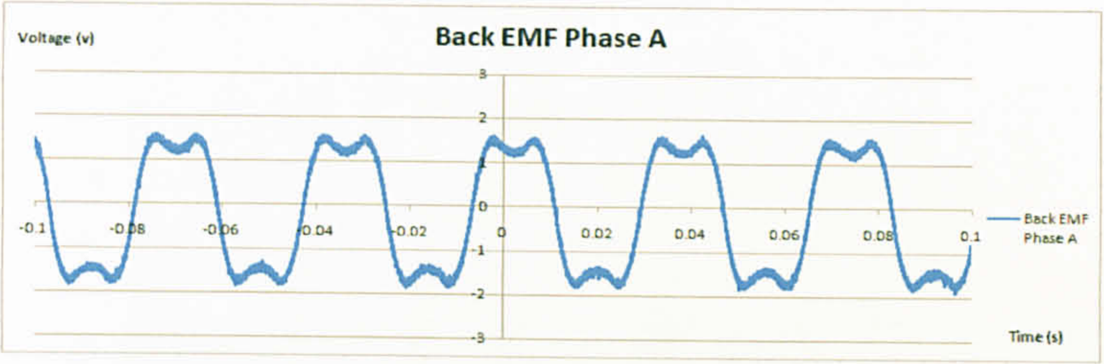


Figure 26: Output of Hall sensor A and Back-EMF phase A waveform

$$\text{Time of one cycle} = \text{time of one period } \times \text{time Hall ON}$$
$$= 36.4 \text{ ms } \times 4 \text{ (in one cycle rotation Hall will ON 4 times)}$$
$$= 145.6 \text{ ms}$$

$$\text{Frequency (Hz)} = \frac{1}{t}$$
$$= \frac{1}{145.6\text{ms}}$$
$$= 6.868 \text{ Hz}$$

$$\text{Speed (rpm)} = \text{Frequency(Hz)} \times 60 \text{ second}$$
$$= 6.868 \text{ Hz} \times 60 \text{ second}$$
$$= 412.08 \text{ rpm}$$

Convert speed, rpm to rad/sec:

$$\text{Speed} \left(\frac{\text{rad}}{\text{sec}}\right) = 412.08 \text{ rev/ min} \times \frac{1\text{min}}{60\text{sec}} \times \frac{2\pi}{\text{rev}}$$
$$= 412.08 \times \frac{2\pi}{60\text{sec}}$$
$$= 43.16 \text{ rad/sec}$$

$$\text{Back EMF constant (per phase)}, K_V = \frac{V_p}{\text{rpm}}$$

$$\text{Voltage} = 3.48 \text{ V}$$

$$K_V = \frac{3.48 \text{ V}}{43.16 \text{ rad/sec}}$$
$$= 0.0806 \frac{\text{V}}{\text{rad/sec}}$$

(b) Test 2: 20 Hz

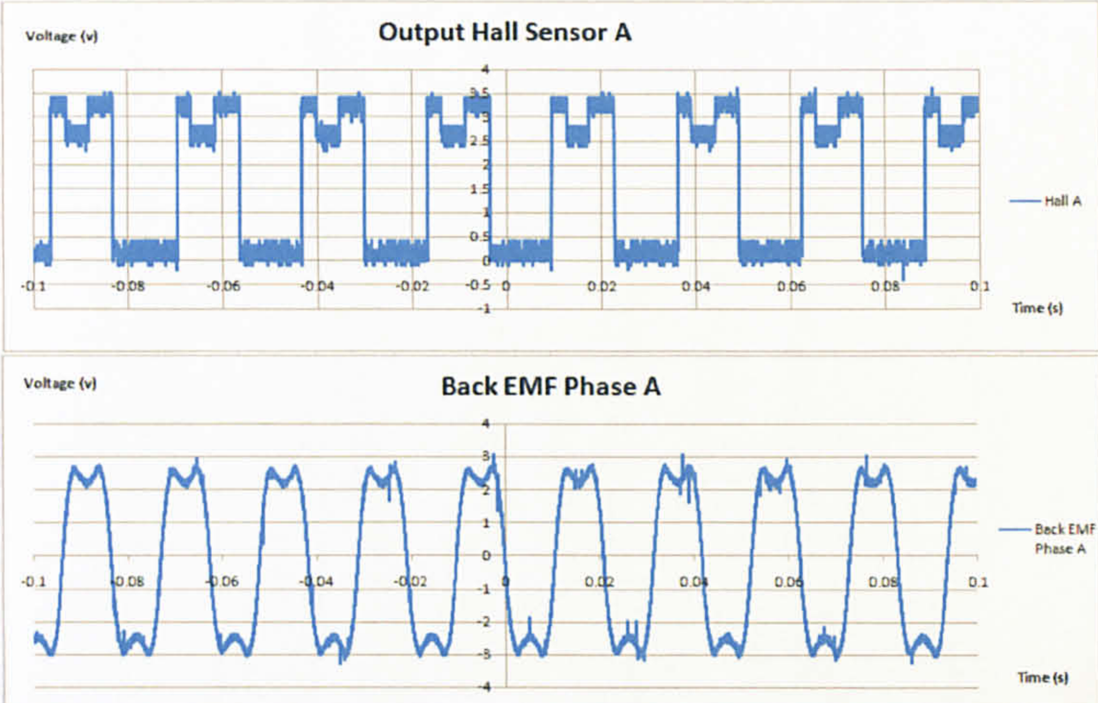


Figure 27: Output of Hall sensor A and Back-EMF phase A waveform

Time of one cycle $=$ time of one period $\times$ time Hall ON

$= 26.5$ ms $\times 4$ (in one cycle rotation Hall will ON 4 times)

$= 106$ ms

$$\text{Frequency (Hz)} = \frac{1}{t}$$

$$= \frac{1}{106\text{ms}}$$

$= 9.4334$ Hz

Speed (rpm) $=$ Frequency(Hz) $\times 60$ second

$= 9.4334$ Hz $\times 60$ second

$= 566$ rpm

Convert speed, rpm to rad/sec:

$$\text{Speed}\left(\frac{\text{rad}}{\text{sec}}\right) = 566\ \text{rev/min} \times \frac{1\text{min}}{60\text{sec}} \times \frac{2\pi}{\text{rev}}$$

$$= 566 \times \frac{2\pi}{60\text{sec}}$$

$$= 59.28\ \text{rad/sec}$$

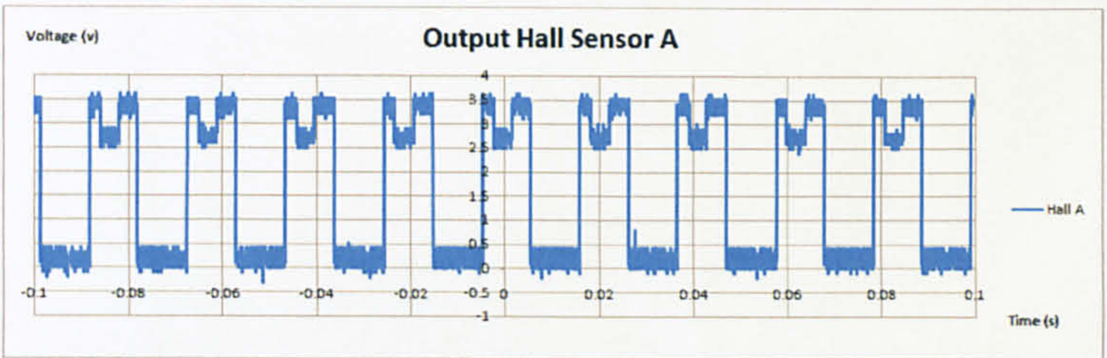
$$\text{Back EMF constant (per phase)}, K_V = \frac{V_p}{\text{rpm}}$$

$$\text{Voltage} = 3.48\ \text{V}$$

$$K_V = \frac{4.6\ \text{V}}{59.28\ \text{rad/sec}}$$

$$= 0.0776 \frac{\text{v}}{\text{rad/sec}}$$

(c) Test 3: 25 Hz



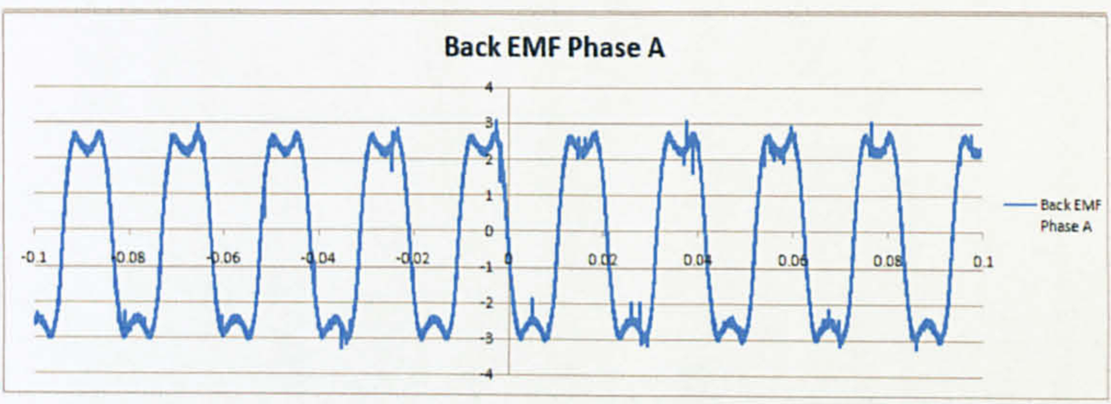


Figure 28: Output of Hall sensor A and Back-EMF phase A waveform

Time of one cycle = time of one period $\times$ time Hall ON

$= 20.08$ ms $\times$ 4 (in one cycle rotation Hall will ON 4 times)

$= 83.2\text{ms}$

$$\text{Frequency (Hz)} = \frac{1}{t}$$

$$= \frac{1}{83.2\text{ms}}$$

$$= 12.0192 \text{ Hz}$$

$$\text{Speed (rpm)} = \text{Frequency(Hz)} \times 60 \text{ second}$$

$$= 12.0192 \text{ Hz} \times 60 \text{ second}$$

$$= 721.15 \text{ rpm}$$

Convert speed, rpm to rad/sec:

$$\text{Speed } \left(\frac{\text{rad}}{\text{sec}}\right) = 721.15 \text{ rev/ min} \times \frac{1\text{min}}{60\text{sec}} \times \frac{2\pi}{\text{rev}}$$

$$= 721.15 \times \frac{2\pi}{60\text{sec}}$$

$$= 75.53\text{rad/sec}$$

$$\text{Back EMF constant (per phase)}, K_V = \frac{V_p}{\text{rpm}}$$

Voltage = 5.84V

$$K_V = \frac{5.84 \text{ V}}{75.53 \text{ rad/sec}}$$

$$= 0.0773 \frac{\text{V}}{\text{rad/sec}}$$

The average of Back EMF constant (per phase), K:

$$\text{Average}, K = \frac{0.0806 + 0.0776 + 0.0773}{3}$$

$$= 0.0785 \frac{\text{V}}{\text{rad/sec}}$$

4.3.5 Control Speed of BLDC Motor by Vary Duty Cycle of PWM Input Signal

A PWM signal is simply a pulse of varying length, in effect a square wave. The experiment is conducted by making the function generator serve as PWM input signal that gives 0 to 5V (+5V is ON and 0V is OFF) input signal to the controller. The maximum voltage output will be +5V and the minimum will be 0V. The length of the pulse generated is characterized by a duty cycle. The duty cycle is the ratio of the signal that the output remains high to the duration of the pulse (ration of t ON to the total time duration of the pulse). For instance, a constant +5V would be equivalent to a 100% duty cycle. 0V would correspond to a 0% duty cycle. The output of function generator is connected to the analog input at the controller which is the +set value and -set value. If the effective voltage is 0V, the motor stops and if the effective voltage is positive until 5V, the motor will move. The amplitude of the applied voltage is adjusted by using the PWM technique - varying the duty cycle. By varying the duty cycle of the PWM input signal the motor can rotate in different speed. Speed can be measured and calculated from the Hall sensor output of the motor. The calculated speed will be compared with the tachometer. The frequency given by function generator to the controller will be fixed at 1 kHz because the author intends to study the effect of varying duty cycle of the PWM input on the speed of motor.

a) First set the input duty cycle of PWM with 25 %. Figure 29 below shows the ON time of PWM input signal is less than OFF time of the input signal (ON for 25 %of the total duration of the pulse).

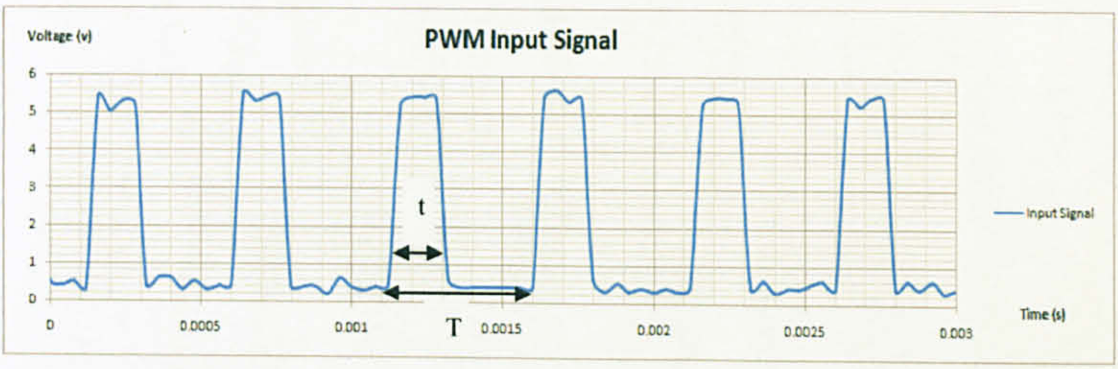


Figure 29: Input signal vary with Duty Cycle of 25%

$$\text{Duty cycle (\%)} = \frac{t_{ON}}{T} \times 100$$

$$= \frac{0.000127}{0.0005} \times 100$$

$$= 25.4\% \approx 25\%$$

The output of Hall sensor is taken with the input signal of duty cycle 25%. This output will be used to calculate the speed of BLDC motor and compared with the tachometer. The output is obtained from any one of three Hall sensors, in this case Hall sensor C. In one full cycle rotation of the motor, there are 15 pulses of the Hall sensor output. Figure 30 below shows the output of Hall sensor C.

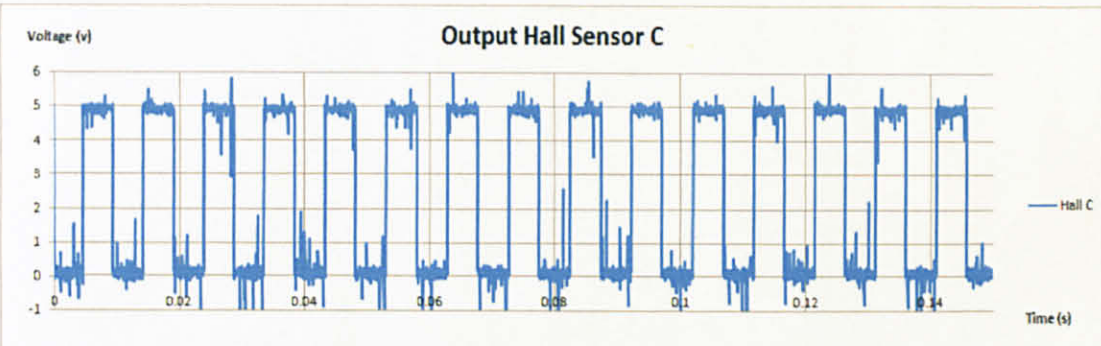


Figure 30: Output Hall sensor C

$$\text{Time of one cycle} = \text{time of one division X num. division per cycle}$$

$$= 40\text{ms} \times 7$$

$$= 296\text{ms}$$

$$\text{Frequency (Hz)} = \frac{1}{t}$$

$$= \frac{1}{296 \text{ ms}}$$

$$= 3.3784 \text{ Hz}$$

$$\text{Speed (rpm)} = \text{frequency (Hz)} \times 60 \text{ second}$$

$$= 3.3784 \text{ Hz} \times 60 \text{ second}$$

$$= 202.704 \text{ rpm}$$

By using a tachometer, the speed measured is 210.05 rpm.

b) Second, fix the input duty cycle of PWM to 50 %. Figure 31 below shows the ON time of PWM input signal is equal to the OFF time of input signal (ON time 50 % of total pulses duration).

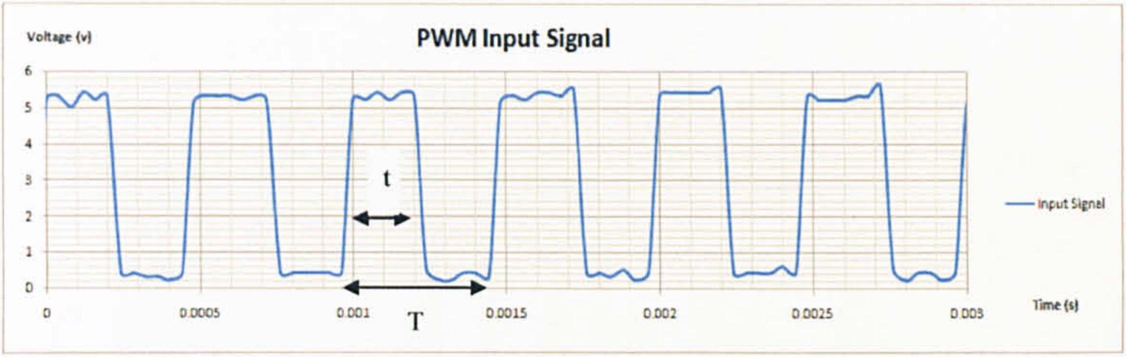


Figure 31: Input signal vary with Duty Cycle of 50%

$$\text{Duty cycle (\%)} = \frac{t_{ON}}{T} \times 100$$
$$= \frac{0.00025}{0.0005} \times 100$$
$$= 50\%$$

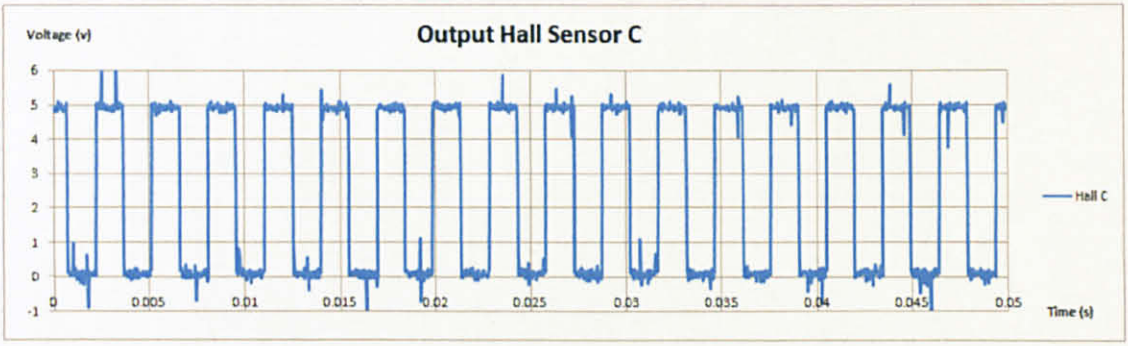


Figure 32: Output Hall sensor C

$$\text{Time of one cycle} = \text{time of one division X num. division per cycle}$$
$$= 10\text{ms} \times 8.9$$
$$= 89\text{ms}$$

$$\text{Frequency (Hz)} = \frac{1}{t}$$
$$= \frac{1}{89 \text{ ms}}$$
$$= 11.236 \text{ Hz}$$

Speed (rpm) = frequency (Hz) $\times$ 60 second

$= 11.236$ Hz $\times$ 60 second

$= 674.16$ rpm

By using a tachometer, the speed measured is 680.54 rpm.

c) Then, set the input duty cycle of PWM at 75 %. Figure 33 below shows the ON time of PWM input signal larger than OFF time of input signal (ON time 75 % of total pulses duration).

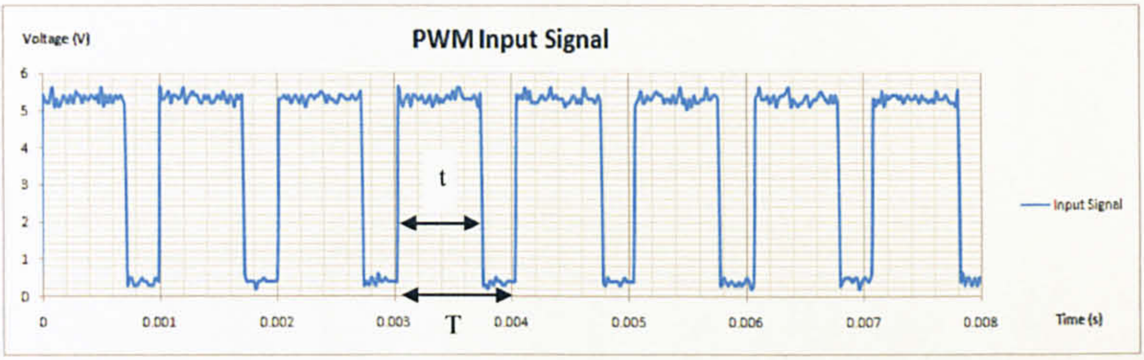


Figure 33: Input signal vary with Duty Cycle of 75%

$$Duty\ cycle\ (\%) = \frac{t_{ON}}{T} \times 100$$

$$= \frac{0.00037}{0.0005} \times 100$$

$$= 74.6\% \approx 75\%$$

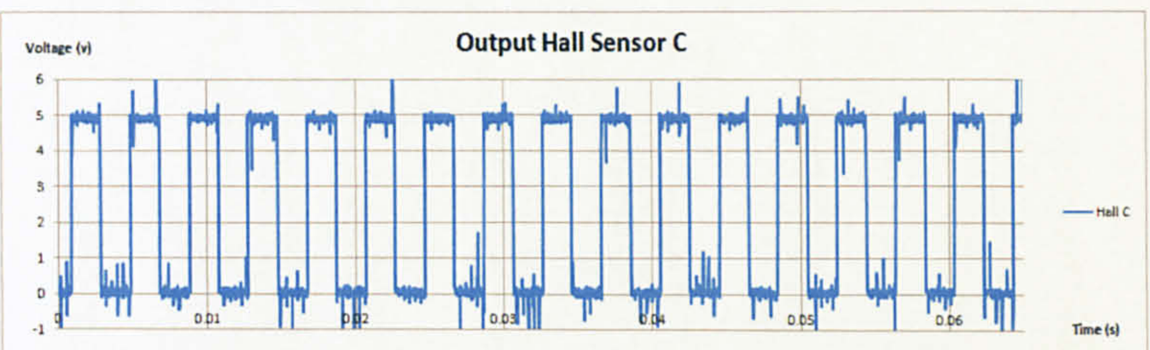


Figure 34: Output Hall sensor C

Time of one cycle = time of one division X num. division per cycle

$$= 10\text{ms} \times 5.9$$

$$= 59\text{ms}$$

$$\text{Frequency (Hz)} = \frac{1}{t}$$

$$= \frac{1}{59\text{ ms}}$$

$$= 16.949\text{ Hz}$$

$$\text{Speed (rpm)} = \text{frequency (Hz)} \times 60\text{ second}$$

$$= 16.949\text{Hz} \times 60\text{ second}$$

$$= 1016.94\text{ rpm}$$

By using a tachometer, the speed measured is 1017.45 rpm.

Table 1: Summary Duty Cycle PWM Signal and Speed

Duty Cycle PWM Signal (%)	Speed (rpm)
0	0
25.4	202.704
50	674.16
74.6	1016.94

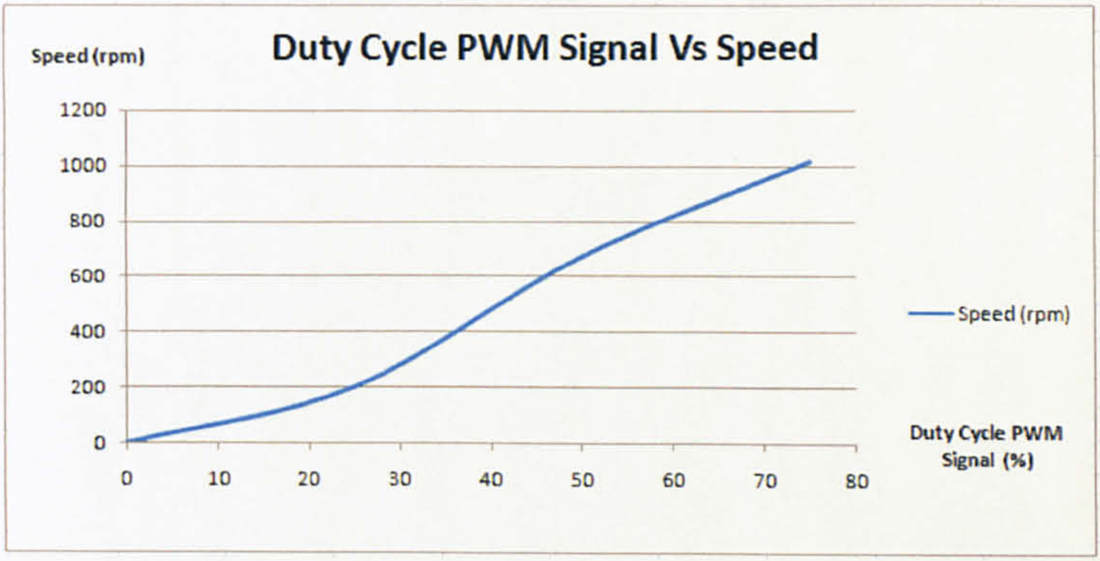


Figure 35: Duty Cycle PWM Signal versus Speed

The Table 1 shows the summary speed of motor when varying the duty cycle of PWM input signal to the controller. Figure 35 shows the graph of duty cycle PWM input signal versus speed. The more ON time of PWM input signal is compared to OFF time of input signal, the higher is the speed of the BLDC motor can rotate and vice versa. As a conclusion, by varying the duty cycle of the PWM signal sent to the motor controller, we can vary the effective voltage of the signal and thereby slow the motor down or speed the motor up depending on the PWM's duty cycle.

4.3.6 Control Speed of BLDC Motor by Varying Duty Cycle of PWM Input Signal using LabVIEW Software

LabVIEW software is a graphical programming language. It uses icons or variables instead of lines of text to create applications or operations. Different with text-based programming language, where instructions determine program execution, LabVIEW uses dataflow programming, where the flow of data determines execution [12]. By using LabVIEW software and external controller hardware which is Compact RIO, the program of speed control can be implemented. Figure 36 below shows the hardware set up of speed control of BLDC motor.

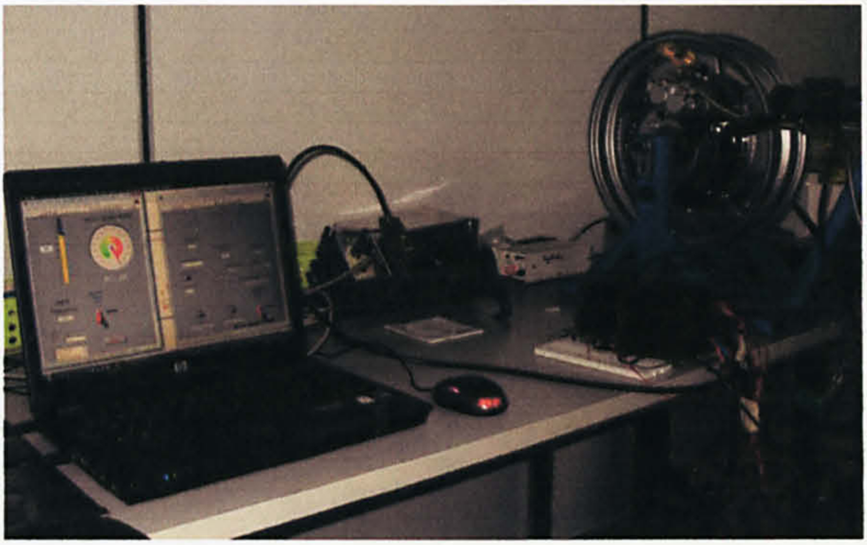


Figure 36: Hardware set up for speed control of BLDC motor

First, develop the programming by using input of the pulse width modulation (PWM) duty cycle that corresponds to the voltage being applied to the BLDC motor. Basically, speed of the motor is directly proportional to the applied voltage. So by varying the duty cycle of the pulse width modulation (PWM) signal, a varying average voltage can be applied to the motor. This average DC voltage determines the motor speed. Figure 37 below shows the front panel of the pulse width modulation (PWM) duty cycle control. This front panel is also known as the user interface. It consists of a set of tools and objects that have code using graphical representations of functions to control the front panel objects. Figure 38 below shows the code of the program.

Figure 37: Front panel of the Pulse Width Modulation (PWM) duty cycle control

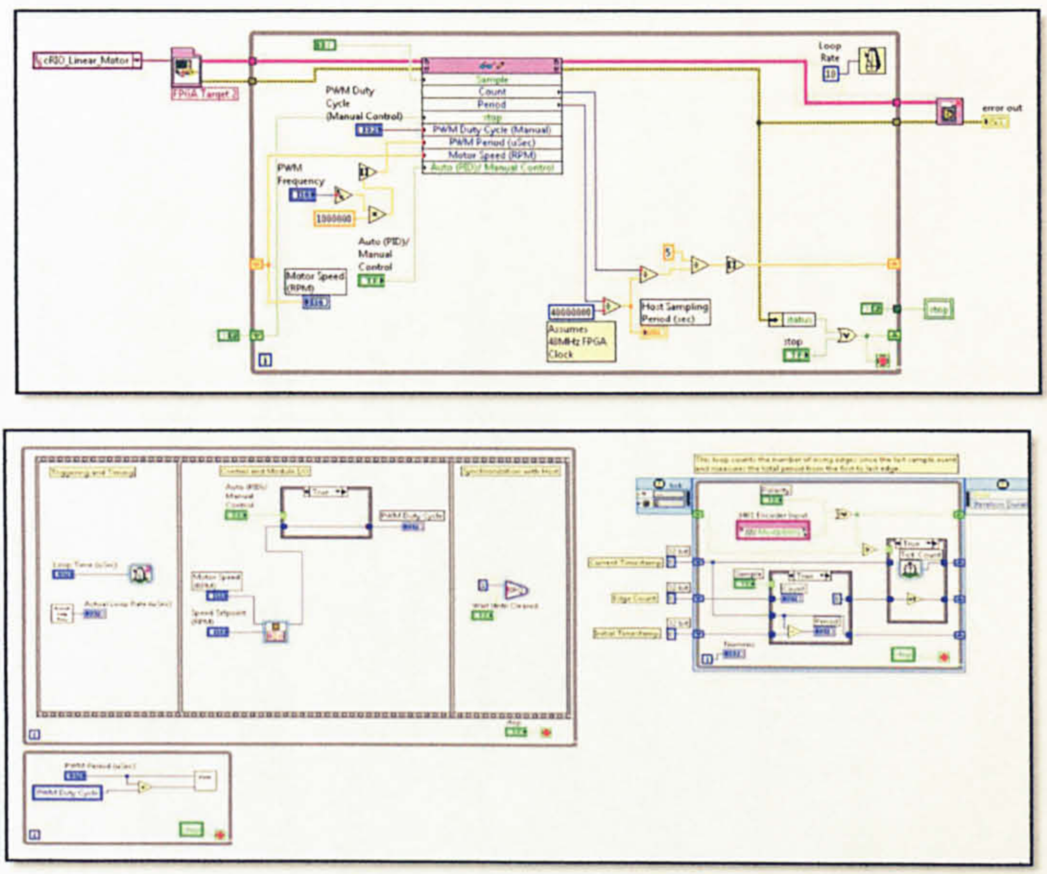


Figure 38: Code of the LabVIEW program

From the output of the Hall sensor, the speed of the BLDC motor can be derived. This output signal is used by the program to analyze or control the speed of motor interface with the Compact RIO controller. The speed of the motor can be displayed on the front panel of the LabVIEW program. Figure 39 below shows the output of Hall Sensor from the BLDC motor. The waveform of Hall sensor obtained is not smooth due to noise interference in the digital signal. If the signal with noise is read by the LabVIEW program, it will generate an erroneous speed measurement. So, the motor cannot run according to the speed required by the user.

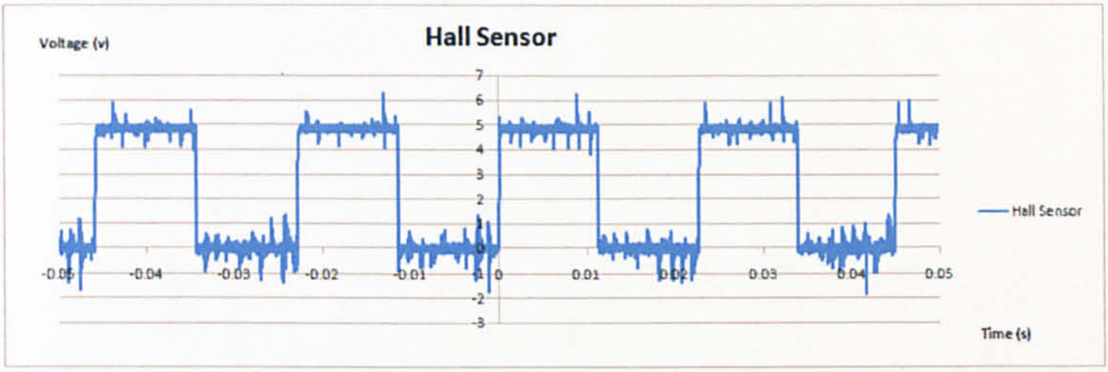


Figure 39: Hall sensor output from BLDC motor

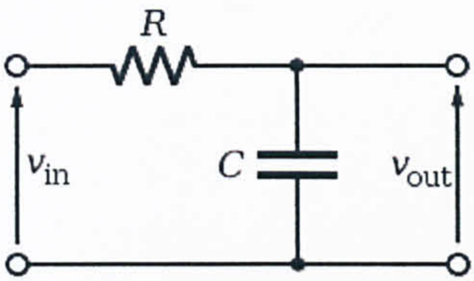
This problem can be encountered by implementing the software lowpass filter in the LabVIEW program itself or connected a RC lowpass filter circuit between the output of Hall sensor from Electrocraft and the Compact RIO controller. The author chooses to design the RC lowpass filter with a cutoff frequency of 10 kHz. Figure 40 below shows the RC lowpass filter circuit diagram.

$$f_c = \frac{1}{2\pi\tau} \ , \tau = \frac{1}{RC}$$

$$f_c = \frac{1}{2\pi RC}$$

Where, cutoff frequency, f_c = 10 kHz

R = 160 Ω , C = 100 nF



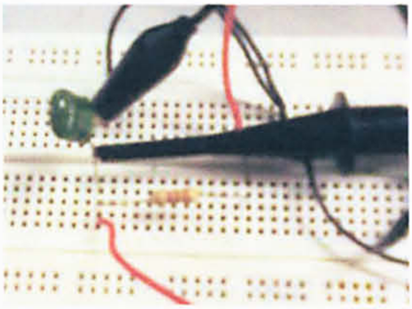


Figure 40: RC lowpass filter circuit diagram

Figure 41 below shows the output of Hall sensor after the RC lowpass filter is connected. The output signal is clean without noise. The program of the LabVIEW can then analyze the signal to obtain the speed of rotation motor and to control the speed of the motor.

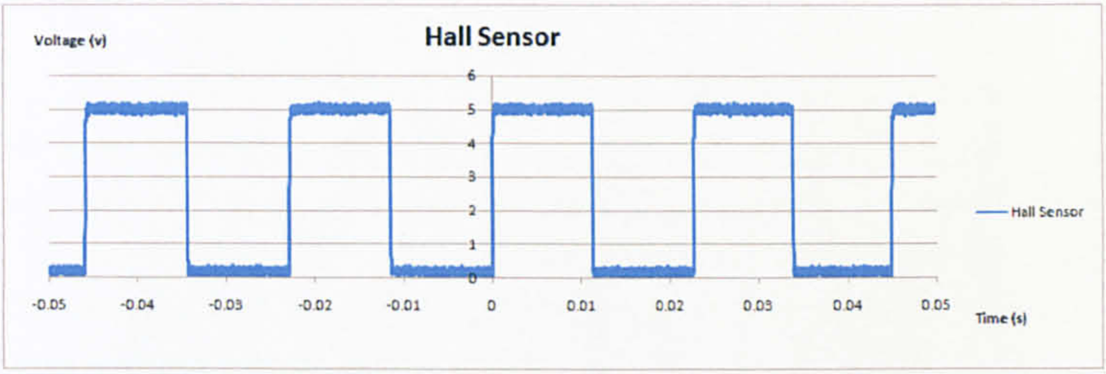


Figure 41: Hall sensor output after passing through the RC lowpass filter

This feedback signal is important for future implementation of PID speed control using the LabVIEW software program. For closed-loop speed control, the actual speed is measured and compared with the reference speed to find the error difference. The actual speed of the motor is obtained from the output signal of Hall sensor. This error difference will be supplied to the PI controller. The output from the PI controller gives the required duty cycle of the PWM signal which will be sent to the Electrocraft controller.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This final report presents the work done by the author and also outcome of the project in studying a 3-Phase Brushless Permanent-Magnet Motor Control for Hybrid Electric Vehicle In-Wheel Motor project. Most of the objectives of studying the operation and control functions of the prototype BLDC in-wheel motor have been achieved. BLDC motor is widely used in industrial applications due to its advantages specifically in term of its higher efficiency compared to the conventional motor. Therefore, it is very important for the electrical engineers to study and familiarize the characteristics of this motor.

It also presents the study of an additional control strategy which is speed control - in addition to torque control that exists in most motor controllers. The author also has learned on LabVIEW software and for the future, intends to implement basic motor control function using this software. Implementation of speed control is ongoing – hardware configuration and software programming – to achieve successful completion. The author hopes the project will be able to contribute towards the industry, especially the automotive industry.

5.2 Recommendation

The project is still continuing toward completion. More research and readings must be done in order to obtain useful information. Therefore, more research must be performed to complete the implementation of a PID speed control. But in the future, the author suggests that programming of speed control can also be implemented using other programming software such as Mat lab/Simulink, and hardware such as embedded targets and PLCs. Data and results obtained using other methods of control can be compared for improvement of the project.

REFERENCES

[1] Brushless DC Motor Control Using the LPC214, Application Note, AN10661, NXP Semiconductors.

[2] Padmaraja Yedamale, Brushless DC (BLDC) Motor Fundamentals, Application Notes, AN885, Microchip.

[3] Brushless DC Motor Control using AT90PWM3/3B, Application Notes, AVR Microcontroller, ATMEL.

[4] Dal Y. Ohm, Jae H. Park, About Commutation and Current Control Methods for Brushless Motor, Application Notes.

[5] Rao S. Zhou, Fukuo Hashimoto, "Highly Compact Electric Drive for Automotive Applications" from Hybrid Electrical Vehicle Technology, SAE International.

[6] Eric Persson (2008), Motor: Drive Decision, Appliance Design, Retrieve from http://www.appliancedesign.com/Articles/Motors/BNP_GUID_9-5-2006_A_10000000000000292917

[7] 4–Q PWM Servo – 30 A, For Brushless-Commutated DC Motors up to 2100 W, User Manual SCA-B4-70-30, Electrocraft Power Innovation.

[8] Leonard N. Elevich 3-Phase BLDC Motor Control with Hall Sensors Using 56800/E Digital Signal Controllers, Application Note, AN1916, Freescale Semiconductor.

[9] Jacek F. Gieras, Mitchell Wing, "Permanent Magnet Motor Technology-Design and Applications", Second Edition, 2002, pg 227-229.

[10] Makoto KAMACHI, Kevin WALTERS, Hiroaki YOSHIDA, Improvement of Vehicle Dynamic Performance by Means of In-Wheel Electric Motors, Technical Review.

[11] Jacek F. Gieras, Mitchell Wing, "Permanent Magnet Motor Technology-Design and Applications", Second Edition, 2002, pg 256.

[12] Electrocraft, BLDC motor, Retrieve from http://www.electrocraft.com/products/bldc/E22/

[13] National Instruments, LabVIEW 7 Express User Manual, 1992-1993 pg 1

APPENDICES

Appendix A: Topology of Brushless DC Motor

No. of poles : 8

No. of turns : 12

No. of coils : 12 (4 coils per phase)

Phase to phase resistance : 0.4 Ω

Peak current : 10 amps

Maximum temperature for core : 150 ° C (insulation limit)

Back EMF : 5.3 v

Voltage RMS : 3.75 v

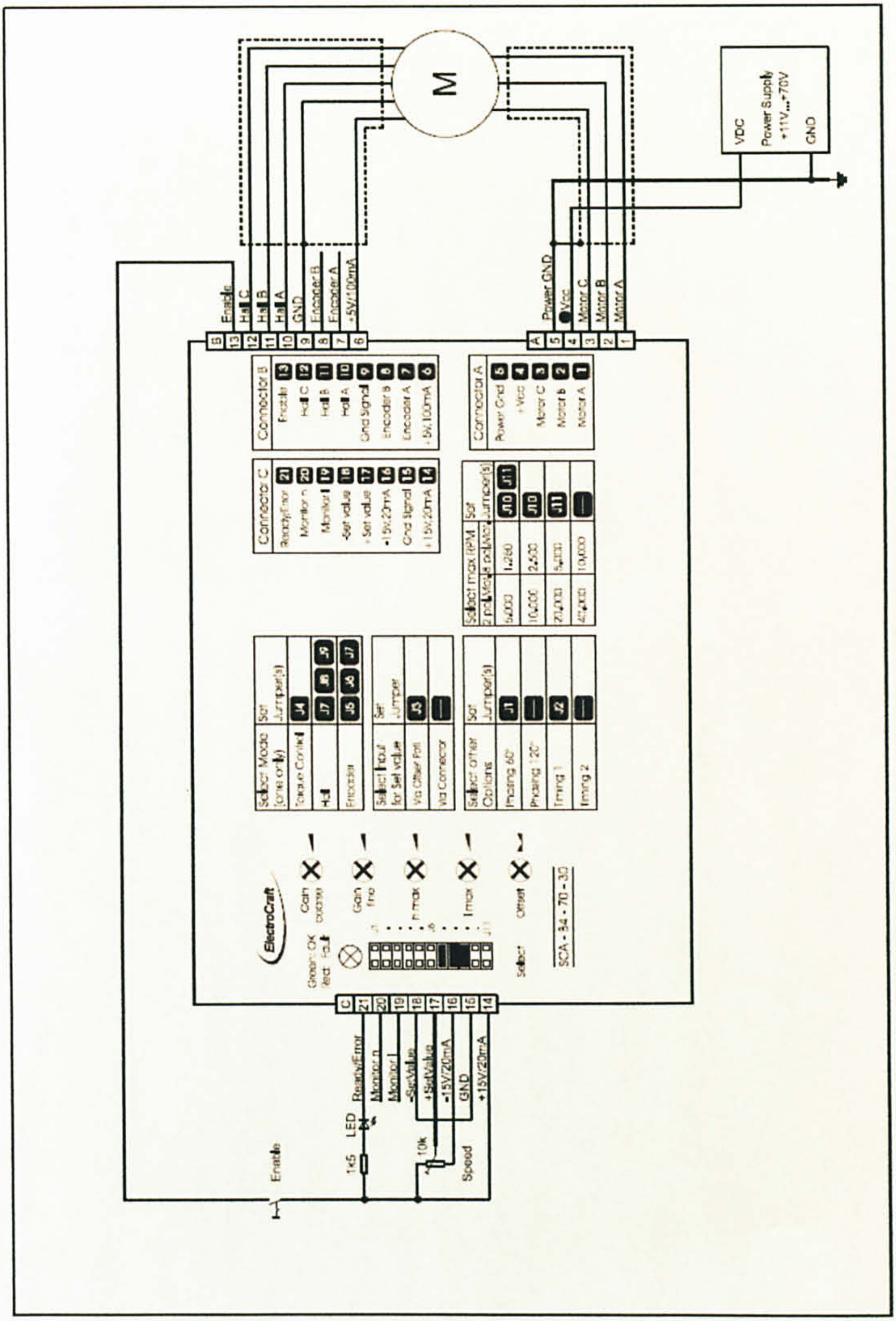
Prediction top speed (no load) : 4500 rpm

Safe operating speed : 2500 rpm

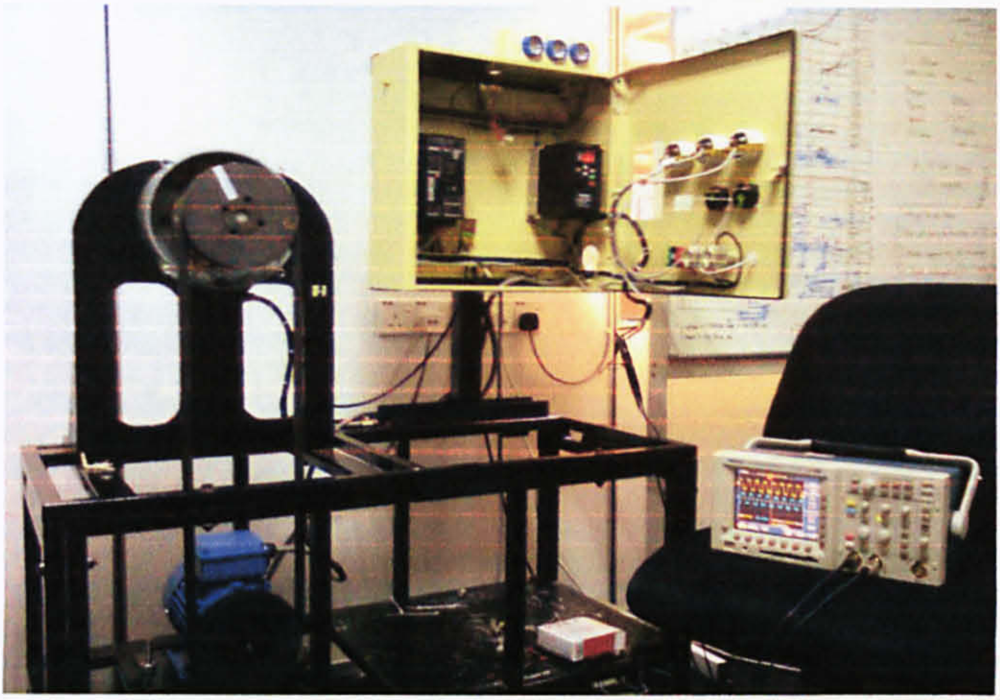
Rotor of BLDC motor

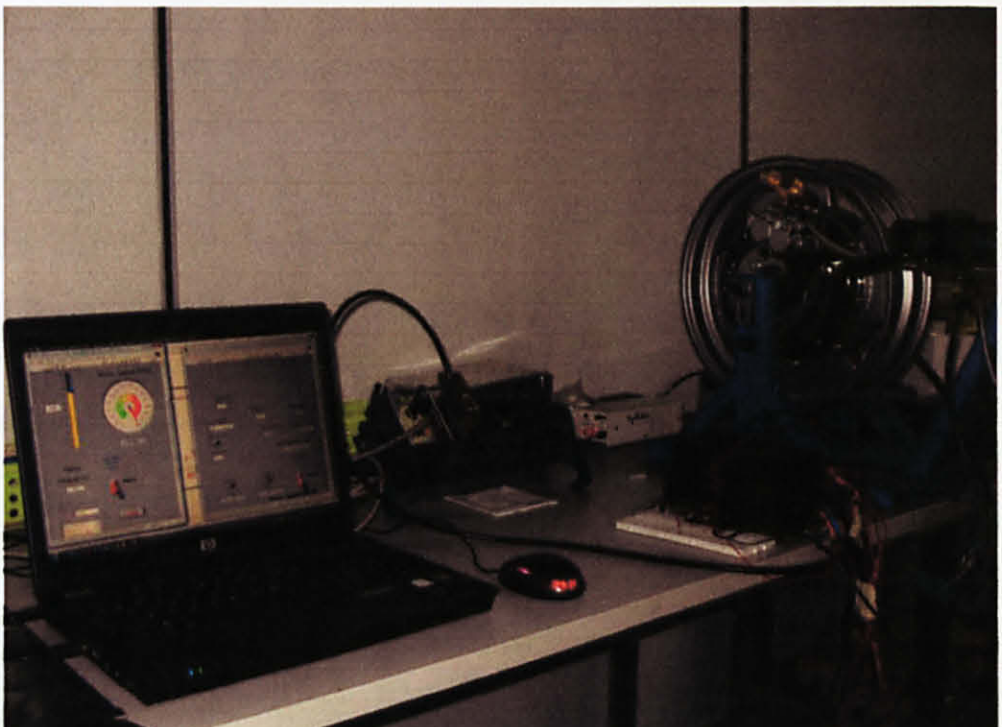
Stator of BLDC motor

Appendix B: Connection diagram of Electrocraft Controller



Appendix C: Experiment of Brushless Motor with Electrocraft Controller





Appendix D: Gantt chart

FYP I

NO.	PROJECT ACTIVITIES	WEEK NO/DATE													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	• Project/Topic Selection														
2	• Data Gathering • Research and discussion on topic • Preparation for preliminary report														
3	• Research and preparation for preliminary report														
4	• Submission of preliminary report														
5	• Research on type of motor controller • Study on Lab View software • Preparation and submission of progress report														
6	• Seminar 1														
7	Project work continue														
8	• Identification and data analysis from the testing • Preparation and data gathering for final report and interim report														
9	• Submission of Final Draft Report	21st October 2009													
10	•Submission of Interim Report	30th October 2009													
11	•Oral Presentation	30th November - 4th December 2009													

FYP II

No.	PROJECT ACTIVITIES	WEEK NO/DATE													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	• Continue project familiarize with the characteristics of BLDC motor • Preparing report for Progress Report 1														
2	• Project continue with experiment and testing of BLDC motor														
3	• Preparing report for Progress Report 2														
4	• Programming of speed control using labVIEW software														
5	• Result obtained from experiment and testing being discussed														
6	• Study and analysis on the results obtained														
7	• Preparing report for Draft and Final Report (Soft Cover)														
8	• Submission of Technical Report	5th May 2010													
9	• Submission of Final Report (Soft Cover)	5th May 2010													
10	• Submission of Final Report (Hard Cover)	25th June 2010													
11	• Oral Presentation	7th June - 10th June 2010													