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SPEED AND TORQUE CONTROLS OF BRUSHLESS DC MOTOR

NAME : MUHAMMAD ADIB BIN MD ROHIM

MATRIC NO : B 011010055

COURSE : 4 BEKE

SUPERVISOR: DR. AUZANI BIN JIDIN

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SPEED AND TORQUE CONTROLS OF BRUSHLESS DIRECT CURRENT MOTOR

MUHAMMAD ADIB BIN MD ROHIM

A report submitted in partial fulfilment of the requirements for the degree of Bachelor of Electrical Engineering (Power Electronic and Drives)

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APPROVAL

"I hereby declare that I have read through this report entitle
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Supervisor's Name : Dr. AUZANI BIN JIDIN

Date : 18 JUNE 2014

DECLARATION

I declare that this report entitle "SPEED AND TORQUE CONTROLS OF BRUSHLESS DIRECT CURRENT MOTOR" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Name : MUHAMMAD ADIB BIN MD ROHIM

Date : 18 JUNE 2014

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ABSTRACT

This project presents the Speed and Torque Controls of Brushless Direct Current (BLDC) motor. Due to the drawbacks of conventional Direct Current (DC) machines which are Brush Direct Current (BDC) motor, the use of BLDC motor is proposed because of its advantageous compared to BDC motor. Even if compared to other machines in industrial, BLDC motor still possessed better performances in term of its control simplicity, high torque density, and lower maintenance. The proposed Speed and Torque Controls is implemented by restrain the current and torque within predefined band gap and also closed loop speed controller by varying the Proportional (Kp) and Integral (Ki) gains. By applying this concept, it required one current loop for the hysteresis to take place but the benefit of this method is that it can force the torque ripple to shut within the band gap. Next, the dynamic response of the Torque Hysteresis Control for BLDC scheme is modelled by proportional integral speed controller. A proper selection of Kp and Ki gains will determine the dynamic response of BLDC drive. Thus, in order to realize the project, a simulation were carried out using MATLAB/SIMULINK and sim-power system blockset simulation. Then, for the experimental, the control system was using the dSPACE in the iDRIVE driver kit. Lastly, based on the results obtained, it is proven that this scheme has good controlling mechanism and suitable for BLDC motor drive. Besides, the implementation of both PI controller and Torque Hysteresis Controller also gives excellent performance for the BLDC motor.

ABSTRAK

Projek ini membentangkan tentang Kawalan Kelajuan dan Tork untuk Motor Arus Terus Tanpa Berus (ATTB). Oleh kerana kelemahan Mesin Arus Terus konvensional iaitu Motor Berus Arus Terus (BAT), penggunaan motor ATTB adalah dicadangkan kerana ia lebih berfaedah jika dibandingkan dengan motor BAT. Malah jika dibandingkan dengan mesin lain dalam industri, motor ATTB masih memiliki prestasi yang lebih baik dari segi kesederhanaan kawalan, ketumpatan tork yang tinggi, dan penyelenggaraan yang lebih rendah. Skim Kelajuan dan Kawalan Tork yang dicadangkan adalah dengan melaksanakan dengan kekangan arus dan tork dalam jurang jalur yang telah ditetapkan dan juga mengawal pusingan kelajuan tertutup dengan mengubah pekali Berkadar (kp) dan pekali Penting (Ki). Dengan menggunakan konsep ini, ia memerlukan satu pusingan arus tertutup bagi histeresis berlaku tetapi kebaikan kaedah ini ialah ia boleh memaksa riak tork untuk menutup jurang dalam band ini. Seterusnya, tindak balas dinamik Tork Kawalan Histeresis untuk skim ATTB dimodelkan oleh pengawal kelajuan penting berkadar. Pilihan pekali Kp dan Ki yang betul akan menentukan tindak balas yang dinamik dalam memacu motor ATTB. Oleh itu, untuk merealisasikan projek ini, simulasi dilaksanakan dengan menggunakan MATLAB/ SIMULINK dan sistem simulasi blok SIM/POWER. Kemudian, bagi eksperimen pula, sistem kawalan adalah menggunakan dSPACE dalam pemandu kit iDrive. Akhir sekali, berdasarkan kepada keputusan yang diperolehi, telah terbukti bahawa skim ini mempunyai mekanisme kawalan yang baik dan sesuai untuk memacu motor ATTB. Selain itu, pelaksanaan kedua-dua pengawal PI dan Tork Histeresis juga memberikan prestasi yang sangat baik untuk motor ATTB itu.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

For decades, Direct Current (DC) motors served in many applications. It is due to the simplicity of its construction, controlling mechanism, and can produce superior dynamic performance. Despite of that, the construction of DC motor that equipped with brushes and commutator can cause some limitations. Furthermore, due to the existence of the brushes and commutator, it requires regular maintenance, cannot operated at very high speed, and usually reduce the life expectancy of Brushed DC (BDC) motor. Thus, the Brushless DC (BLDC) motor were developed to overcome deficiency of the Brushed DC motors.

However, Brushless DC (BLDC) motor requires proper controller as it uses electronic commutator for its operation. Thus, this report is about the research on Speed and Torque Controls that will be used to control the motor. The project has started with simulation profile for the control scheme in FYP 1 and experimental of the algorithm using dSPACE in FYP 2. Next, both simulation and experiment results have been compared to verify its significant.

1.2 Project Motivation

DC motors were known for their efficiency and reliable characteristics that are suitable for many applications. Unlike AC motors, DC motors able to operate at a fixed speed for a fixed voltage. Yet, one of the conventional DC motors is Brushed DC motor have many drawbacks on its mechanical compartments. It requires both brushed and commutator for its operation where its limit the capabilities of the motor. Thus, the BLDC motors is proposed to overcome the drawbacks of conventional dc machines.

From the reviewed methodology of the controlling mechanism, it is showed that the conventional method needs many improvement in order to improve the speed control performance of the BLDC machines to its fullest. Compared to the previous control algorithms, the proposed Speed and Torque Controls is chosen as it gives better controlling mechanism on the speed, phase currents and torque of the BLDC motors by varying Kp and Ki of PI speed controller. Besides, amongst the conventional methods are voltage control and PWM control which has its own characteristics. However, both of it gives a very high current overshoot when operating the machines. Thus, Torque Hysteresis Controller is introduce due to its advantages which is it able to handle the drawbacks because the method has inherent over-current protection that is always being monitored. Furthermore, the dynamic response of the BLDC provided by proportional integral speed controller gives the fullest operating condition of the machines.

1.3 Objectives

The objectives of this project are:

i. To model and simulate the Speed and Torque Controls of BLDC motor using MATLAB/SIMULINK.
ii. To verify the Speed and Torque Controls of BLDC motor via simulation and experimentation.

1.4 Scope Of Project

The main scope of this project is to control Speed and Torque for BLDC motor using PI speed controller and Torque Hysteresis Controller respectively. This project is proposed to improved the speed performance by selecting appropriate values of Kp and Ki gains. Besides, it is important to develop the model of BLDC motor for further understanding. Next, for the final stage of the project, the simulation model of Speed and Torque Controls for BLDC motor using MATLAB/SIMULINK must be analyse and compared with experimental result to verify the efficiency of the scheme. The experiment was conducted using iDRIVE controller that equipped with dSPACE, Voltage Source Inverter (VSI), Gate Driver, Decoder, and Current Transducer.

1.5 Report Outlines

Chapter 1 is mainly about defining the objectives and scope of the project. All the consideration have been taken into account to ensure the project achieved the objectives. The project background and motivational project also been discussed in this chapter. This is the most important part to ensure that the vision of the project is clearly understood.

In chapter 2, a brief literature review has been done to study the theoretical views of the machines used and all the related previous works. Besides, the construction and operation of the BLDC motor also been analysed. Lastly, all the conventional control techniques has been study to ensure a better understanding on the executed project.

Next, for chapter 3, the methodology of the project were clearly discussed. This is to make sure that the process of conducting the project are in the right track and follow the order. The process includes determining the switching state for the inverter and decoding Hall Effect signals scheme. Besides, the tests such as the torque test also have been done to the real motor to evaluate the capabilities of the motor.

Generally, chapter 4 is related about the discussion on the obtained result. Results from the simulation and experiment were analyse to observe its performance. The characteristic of the results will indicates either it has obtained the desired output of the proposed control scheme.

In chapter 5, the findings and outputs of the project have been concluded. This is important to analyse and verified either the proposed project achieve its target. Besides, the recommendations for better control scheme also been proposed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is generally about to study and analyse the related information and previous works on the related topics. It is compulsory to fully understand the theoretical and concepts of both BLDC motor and drives to ensure that the project can accomplished and meet the objectives.

2.2 Basic Topologies

2.2.1 Construction of BLDC Motor

A BLDC motor is constructed with two main parts that is a permanent magnet rotor and wire wound stator poles[1]. This construction distinguishes between BLDC and BDC motor where BDC motor constructed such that its stator generates a stationary magnetic field that surround the wired wound rotor. Magnetic steel sheets is preferred to construct the stator magnetic circuit. The stator phase windings are normally wound as one coil on the magnetic pole or can even be inserted in the slots[2]. Since this motor is implement partially both conventional ac and dc machines, it cannot be classified to either one of it even though it is powered by a direct current(DC)[3]. Next, BLDC motors may have any number of phase windings but generally it were designed in single phase , two phase, and three phase configurations. However, three phase configuration motors connected in star connection are the most popular and widely used due to its efficiency and low torque ripple. Theoretically, the higher the number of phase windings will improve the electromagnetic torque quality but infinite number of phase windings is not appropriate in practice[2].

As mentioned, BLDC motors did not consists of commutator and brushed as BDC motors to operate. This motor requires controller that is an electronic commutation in order for it to supply commutated current to the motor windings synchronized to the rotor position[4]. As the magnetic field at the stator will change due to the current polarity changes in the slots windings. Thus, the current polarity must change accordance to the rotor magnetic field which requires the rotor position to be traced[3]. In order to specify the rotor position, a feedback position sensor is readily mounted or embedded in the BLDC motor that is known as Hall Effect sensor. Hall sensor used to detect the rotor position in order to determine which stator winding that will be energized in proper sequence[1]. The cross section of BLDC motor with respect to the embedded Hall Effect sensor.

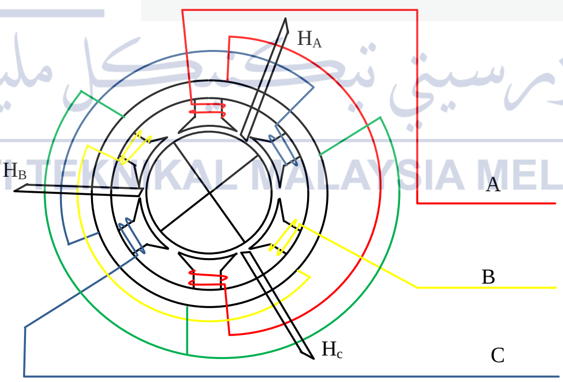

Figure 2. 1 : Cross section of BLDC motor with respect to Hall Effect Sensor

2.2.2 Operation Of BLDC Motor

The BLDC motor is constructed by a three phase star connection windings and ungrounded neutral point[5]. However, it operated as if it is designed in two phase connection. Depending on rotor position, only two of the inverter legs will be energised at particular time[6]. Where, the third leg is kept inactive at the same time. Each sequence shown in Figure 2.3 rotates at 60 electrical degrees. One full 360 degree rotation six step voltage source inverter need 6 sequence with only one current path for each sequences[7]. In Figure 2.2 below shows the correlative of back emf, phase currents, and Hall effect signals relatively.

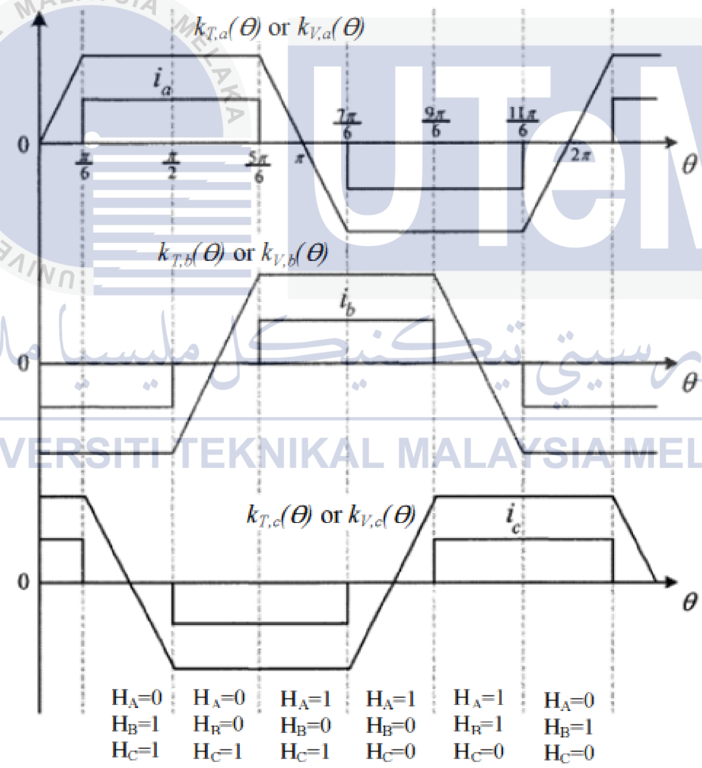

Figure 2. 2 : Ideal back-emf’s, phase currents, and Hall Effect signals

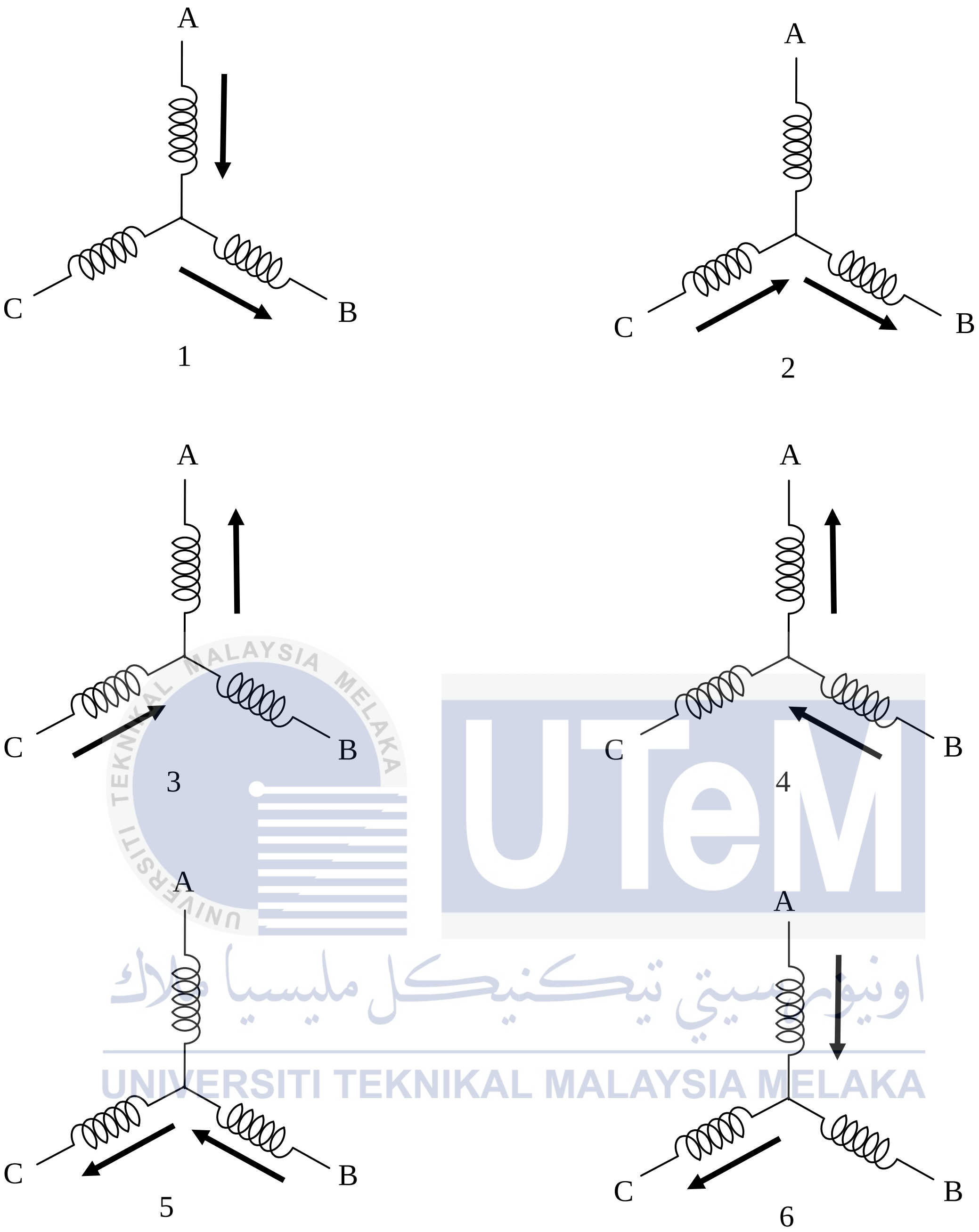

Figure 2. 3 : Winding energizing sequence

2.2.3 Stator Winding Variants

2.2.3.1 Trapezoidal Motors

As the name indicate, the trapezoidal motor produce a back Electro Motive Force(EMF) in trapezoidal shape. In addition, due the trapezoidal shape of the induced back EMF in the stator winding, its phases needs to be supplied with quasi-square currents for ripple-free torque operation. Even though the torque output produce by sinusoidal motors smoother than a trapezoidal motor, but it can gives higher efficiency, torque output is constant and proportional to currents amplitude, simple and lower cost. It also has been chosen as the motor that to be used in the project.

2.2.3.2 Sinusoidal Motors

Whereas for sinusoidal motors, it requires sinusoidal phase current for ripple-free torque operation as it generates sinusoidal shaped of the back EMF. Despite of its smooth torque output, it comes with several drawbacks because requires complex software and hardware compare to trapezoidal motors. Besides, the rotor position should be detected at every time instant, thus it should be equipped with high resolution position sensor.

2.2.4 Hall Effect Sensors

Hall effect sensor is a magnetic field sensor that capable to be implement as principle component in lots of other types of sensing devices such as current, pressure, and position. In the utilization of BLDC motors, Hall effect sensor that generally used are position sensor type. To ensure that the BLDC motors rotate smoothly, the energized stator windings should be in the right order. Thus, the embedded Hall Effect sensor in the stator act as the detector to determine the rotor and sector on which the rotor is presently located position during the motor operation. A three bit code is generated by the sensor with the values ranging from 1 to

6 respectively[8]. The produced code value is then gives information on which winding should be energize for the next sequences.

Mostly, in each of BLDC motors are mounted with three Hall sensors in the stator at the non-driving end of the motor. The sensors are placed with equal distance from one another by 60 electrical degrees to ensure that each sensors output is aligned with either one of the electromagnetic circuit[8]. A digital high level for the first 180 electrical degrees of electrical rotation will be produce while the rest of 180 electrical degrees will outputs a low level[8]. This digital levels are generate by each of the sensor elements. The Hall sensor will interpreted either high or low signal each time when the rotor magnetic poles pass near the sensors. Thus, this process will show either North or South pole that is passing close to the sensors.

However, the signals that are either low or high must be decoded to respected signals as shown in Table 2.1. Only then, the decoded signals can generate the reference current that will be used for the control scheme.

Table 2. 1 : Hall Effect decoded signals

Hall Effect Signals			Decoded Signals		
H_A	H_B	H_C	H_A'	H_B'	H_C'
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

2.3 Related Previous Work

2.3.1 Topologies Of Control Strategy For BLDC Motor

This section will discussed about the schemes that applicable for BLDC machine. All the concepts and operation works being compared to each other for better understanding on controlling BLDC motor.

2.3.1.1 Voltage Control

Voltage control strategy implement the theory that speed of BLDC motor is directly proportional to the voltage applied to the motor terminals[3]. The speed of the BLDC motors are achieved by varying the voltage source that supplied to the motor. As the higher the voltage source, the faster the speed of the motor. This control strategy did not consist any current control loop, hence there are no current sensors used in the drive. Besides, this strategy is less cost compared to pulsed power stage which is the PWM. However, a linear power stage gives out high losses at high current and low voltage.

2.3.1.2 PWM Control

Pulse Width Modulation(PWM) applied the concepts of controlling the average output voltage from a fixed input voltage[3]. The theoretically of PWM control can be explained clearly by the concepts of basic switch mode dc to dc converter. Where, the average voltage depends on the switching at the converter. PWM can be classified into either variable or constant switching time period based on the switching nature. If the switching time period is constant, it indicates the constant frequency PWM control. Otherwise, it is known as variable frequency PWM control when the switching time period is can be varied. By having a constant frequency in the PWM control, the filtering process much easier as the harmonics are produced in multiples at the switching frequency. Differ from variable switching frequency where it is completely difficult to filter the harmonics under any circumstances.

However, in practice, the load will be resistive-inductive. As any case, when the current passing the inductors, it is forced toward zero in a short time, inductive load may damage the switches and resulting very high voltage spikes[3]. Thus, it needs a diode labelled as free wheeling diode to eliminate the high voltage spikes by allowing the current to naturally go down towards zero. This add the drawbacks of the PWM.

PWM approaches in producing signals are by comparing the voltage control with a sawtooth carrier signal. The switching signal describes as follow:

$$\text{Switching signal} = \begin{cases} Vcontrol > Sawtooth\ signal & ,switch\ turned\ on. \\ Vcontrol < Sawtooth\ signal & ,switch\ turned\ off. \end{cases}$$

2.3.1.3 Torque Hysteresis Control

In Torque Hysteresis Control (THC) strategy, there will be one current control loop for the structure. The control scheme implement inner current control loop by using DC link current[6]. Two of the three phase currents were measured and then fed to the DC link current. By doing this, the reference currents can be generated. However, it is important to ensure that the sum of phase currents is zero to enable this concept being used. This method suits the BLDC motor because it is designed with three phase star connection with an ungrounded neutral point. Using this scheme, an efficient and high torque dynamic response of the electric machines can be achieved. Besides, the advantage of using this technique is that from the phase currents, the torque were directly determined[1]. The production of DC link current and torque are given as in equation 2.1 and equation 2.2 respectively.

$$\mathrm{I_{ref}} = \frac{\mathrm{T_{ref}}}{\mathrm{k_t}} \tag{2.1}$$

$$\mathrm{T_{e,total}} = \mathrm{T_{e,a}} + \mathrm{T_{e,b}} + \mathrm{T_{e,c}} = \mathrm{k_{t,a} i_a} + \mathrm{k_{t,b} i_b} + \mathrm{k_{t,c} i_c} \tag{2.2}$$

Where,

i_a, i_b, i_c = Phase currents

k_t = Torque constant for phase windings

As discussed earlier, in order to generate the desired torque, it can be directly determine from the reference currents. Besides, the reference currents also will determined the motor currents that needs to be varied.

2.3.1.4 Field Oriented Control

Field Oriented Control(FOC) is generally a vector control technique. The control scheme is to develop a zero value of the d-axis current, i_d. This is to ensure that the direct axis flux linkage will only dependent on the flux linkage by permanent magnet rotor. Besides, this control strategy is also to create a control loop to the voltage source inverter that will then supply the BLDC machine[9]. This will add the reliability of the controller. Next, in order to restrain the id at zero level, the signal derived from the d-axis component of the armature current is designed to be feedback through the P controller[9]. It is then fed to the summing junction that where the integral of the motor angular speed added to it. In results, the initial angle of application of the stator voltage was manipulated.

2.3.1.5 Direct Torque Control

The earlier Direct Torque Control scheme has been introduced in 80's by both Noguchi and Takahashi[10]. DTC strategies are one of the control schemes that has been used since then due to its characteristics. They can gives direct control on the electromagnetic torque and stator flux through an appropriate selection of the inverter control signals. Added to its advantages is the high torque dynamics. So far , Leong and Zhu has successfully proposed the most recent and high performance control strategy[11].

As the time passed over decades, a new control scheme that allow annihilation of previous conceived limitations. This includes considering the rotations, either clockwise or anticlockwise. Besides, due to implementation of three level torque controller, further extinction of torque ripple during sequence to sequence commutations can be obtained[12]. However, the drawback of this technique is caused from its complexity compared to THC method. Thus, by implement THC strategy for BLDC machine, the flux loop can be eliminated and hence create a simpler control design[11].

2.3.2 Topologies of Speed Controller for BLDC

Speed controllers is the closed loop system which provide a reference torque as the output. From the variable parameters that can be varied in the speed controllers, it then generate the desired reference torque that is then turn to converted reference current via the relationship of torque is directly proportional to current. By dividing the reference torque with torque constant(Kt), the reference current is then created and fed to the Hysteresis Controller. Thus, a proper selection of the speed controller is important to enhance the performance of BLDC machines.

2.3.2.1 Proportional Integral (PI) Controller

The proportional integral (PI) controller is one of the famous speed controller and widely used in industrial. This is due to its simplicity in design and structure. Figure 2.4 below shows the block diagram of PI speed controller.

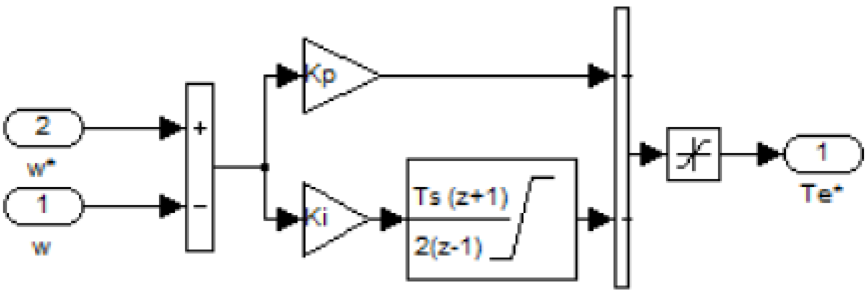

Figure 2. 4 : PI speed controller block diagram

The transfer function of PI controller is given by:

$$V_c(t) = K_p e(t) + \int_0^t K_i \, e(t) dt \tag{2.3}$$

Where,

$V_c(t)$ = Output of PI controller

K_p = Proportional gain

K_i = Integral gain

$e(t)$ = Instantaneous error signal

The proper selection of both proportional and integral gains is important to exhibit a perfect system. The system will become unstable if the Kp is set up at very large value. In contrast, the system response cannot get to the set point in the suppose time[13]. This is due to the low value of the Kp. Besides, proportional controller also produces steady state error. Whereas for the integral controller part, when it is added to proportional parameter, it will able to eliminate the steady state error in the system.

Despite of that, the main disadvantage of integral parameter is that it could lead the system to be saturated[14]. To avoid the occurrence of the saturation is by placing limiter to the integral part. Only then, the output of the integral controller can be add to proportional controller's output.

2.3.2.2 Fuzzy Logic Controller

Fuzzy Logic can also be used as the speed controller for BLDC motor. In order to implement fuzzy logic as controller, it will involve rule base, fuzzification, and defuzzification[15]. Fuzzification involves the process of transforms the input to the fuzzy linguistic variables. Next, rule base is the collection rules that is crucial for designing conclusion. The linguistic controller used in rule base are in the form of logical implication such as "if-then' format[16]. Then, for defuzzification, generally this process is the reverse action of fuzzification. The block diagram system of fuzzy logic shown in Figure 2.5 below.

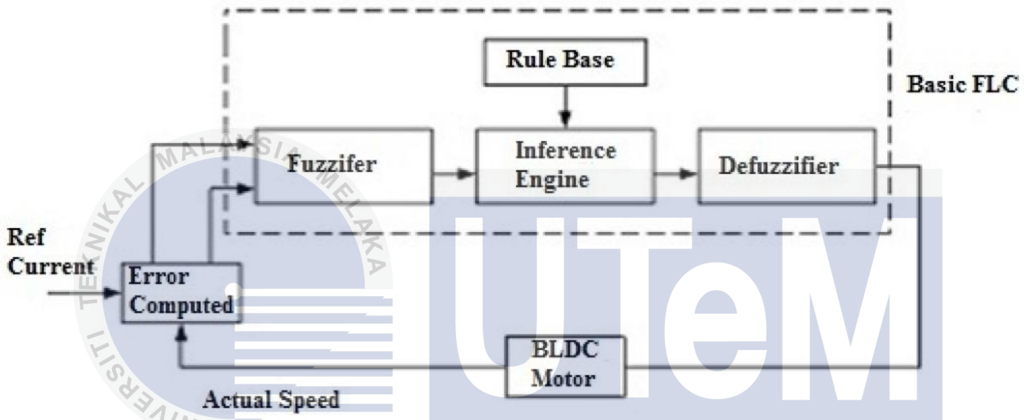

Figure 2. 5 : Fuzzy Logic System

Fuzzy logic functions may vary in many membership forms. Amongst of the forms are a trapezoid, a bell, and a triangle[16]. Next, for the function of fuzzy logic also illustrated in Figure 2.5. The fuzzy logic takes both reference and actual speed as its inputs. Based on that inputs, speed error generated by comparison between those inputs. The fuzzy logic controller able to reduce the transient response at the beginning phase and stabilize it at a short time. Besides, the fuzzy logic was introduced because of its capabilities to ensure that the actual speed follow the reference speed accurately[17]. Next, for the rule base of fuzzy logic, it has been define as shown in Table 2.2.

Table 2. 2 : Rule Base of Fuzzy Logic

u		Ce NS	Ce Z	Ce PS
e	NVB	NVB	NVB	NB
	NB	NB	NVB	BN
	NM2	NM2	NVB	BN
	NM1	NM1	NM2	NM1
	NS	NS	NM1	NS
	Z	Z	PS	PM1
	PS	PS	PM1	PM2
	PM1	PM1	PM2	PB
	PM2	PM2	PVB	PVB
	PB	PB	PVB	PVB
	PVB	PVB	PVB	PVB

Where : -

PVB : Positive Very Big, PB : Positive Big, PM2 : Positive Medium 2, PM1 : Positive Medium 1, PS : Positive Small, NS : Negative Small, NM1 : Negative Medium 1, NM2 : Negative Medium 2, NB : Negative Big, NVB : Negative Very Big, Z : Zero

2.4 Summary Of Review

Based on the conducted literature review, the basic construction and operation of the BLDC machines have been discussed. Then, the energizing sequences for the windings as well as the Hall Effect sensor decoding operation also been overview in this chapter. It is noted that the relative decoded signals are essential in controlling the BLDC motor for excellent performance.

Besides, the variation of control strategies also have been analysed to compared the characteristics each of the control scheme. The controllers used for BLDC machines have their own strategy and method. The only differs them are their simplicity and the performance of BLDC motor that will achieve through implementation of the controllers. However, from the reviewed control strategies, the reliability of the method is important to ensure that the provide the optimum performance for the machine. But, the lower cost and simplest scheme were preferred in any system. Despite of the simplicity of the method, the effectiveness of the scheme also need to be taken into account.

Next, for the speed controllers, there were several method studied to have better information and knowledge about the existing speed scheme. However, this project only cater and covered for conventional PI speed controller even though there are other scheme which provide better performance.

Thus, THC was chosen due to its good characteristics compared to other control schemes. It is dependable but yet have simple method compared to DTC and FOC. Besides, it also exceeds both of voltage control and PWM in terms of the effectiveness that need to be implemented in a controller.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section will discuss about the flow structure in completing this project. It is important to be clearly understand about the process, structure, simulation, and experiment of the Speed Loop of THC for BLDC motor. The research was began with complete analysis and modelling on BLDC motor concepts. Apart of that, the related previous works of the scheme were demolished to obtain the best control strategy for the BLDC motors. Then, the simulation of the drive is designed using Matlab/Simulink. With the arrangement of the simulation blocks, the simulation is generated by tuning all the parameters in order to obtain the perfect system.

Next, the experimental of the scheme was carried out to produce the actual output or performance of the drive. Using the available iDRIVE in the Power Electronics Laboratory, the experiment was runs using the dSPACE in the iDRIVE. The topology of the project are discussed in the following sections.

3.2 Modelling Of Brushless DC Motor

The dynamics model of BLDC machine are described by the set of mathematical differential equations as follow. The construction of the BLDC motor had been discussed on the previous Chapter 2. Basic circuit analysis to obtain per phase voltage was used for derivation of electrical equations as shown by equation 3.1.

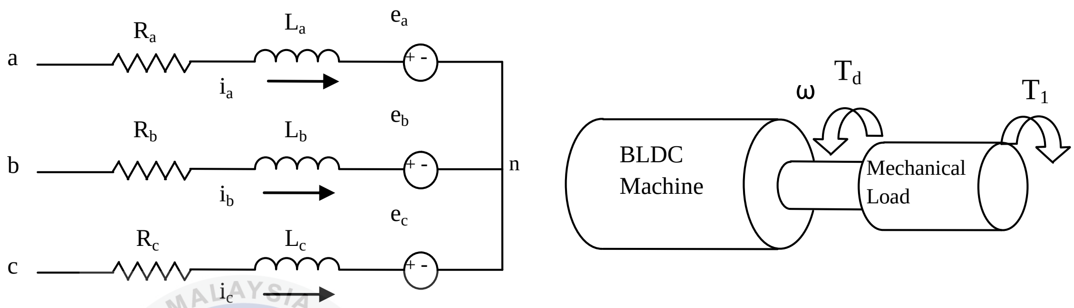

Figure 3. 1 : Three phase equivalent circuit and mechanical model of BLDC machine

Electrical equation:

$$V_{an}(t) = i_a R_a + L_a \frac{di_a(t)}{dt} + e_a(t) \tag{3.1}$$

Where,

$V_{an}(t)$ = per phase voltage

$i_a(t)$ = per phase current

$e_a(t)$ = per phase voltage back-EMF

R_a = per phase resistance

L_a = per phase inductance

Mechanical equation:

The mechanical equation that describes the machine's angular velocity to the produced load torque, electromagnetic torque, and motor parameters is shown in equation 3.2.

$$T_{em}(t) = \omega(t)b + J\frac{d\omega}{dt} + T_L(t) \quad (3.2)$$

Where,

$T_{em}(t)$ = Developed electronic torque

$\omega(t)$ = Rotor angular velocity

b = Viscous friction constant

J = Rotor moment inertia

T_L = Load torque

$$T_d = k_{t-a}i_a + k_{t-b}i_b + k_{t-c}i_c \quad (3.3)$$

$$e_a = k_e\omega(t) \quad (3.4)$$

Where,

k_{t-x} = per phase torque sensitivity

k_{e-x} = per phase back EMF

Voltage equation in laplace domain:

$$V_{an}(s) = R_aI_a(s) + L_asI_a(s) + K_e\omega(s) \quad (3.5)$$

Electromagnetic torque in laplace domain:

$$I_a(s) = \frac{V_{an}(s) - K_e\omega(s)}{R_a + sL_a} \quad (3.6)$$

$$T_{em}(s) = k_tI_a(s) \quad (3.7)$$

$$T_{em}(s) = Js\omega(s) + b\omega(s) + T_L(s) \quad (3.8)$$

$$\omega(s) = \frac{T_{em}(s) - T_L(s)}{b + sJ} \tag{3.9}$$

Torque equation:

$$T_{em}(s) = K_t \frac{V_{an}(s) - K_e\omega(s)}{R_a + sL_a} \tag{3.10}$$

Transfer function:

$$\frac{\omega(s)}{V(s)} = \frac{\frac{K_t}{JL_a}}{s^2 + \frac{(JR_a + BL_a)}{JL_a}s + \frac{(BR_a + K_tK_e)}{JL_a}} \tag{3.11}$$

3.3 PI Controller

A proportional-integral controller (PI controller) is a control loop feedback mechanism that is used widely in industrial control systems. The PI controller process the error of the comparisons between the actual and reference speed. The higher the error, more unreliable the controller. For experimental, the actual speed was measured using speed/position encoder.

3.3.1 Proportional Parameter

The proportional parameter controls the output of a system that is proportional to the current error value. By multiplying the error by a constant Kp, the proportional response can be tuned for a perfect system. The proportional parameter is given by:

$$P_{out} = K_p e(t) \tag{3.12}$$

Where,

P_{out} = Output of Proportional controller

K_p = Proportional gain

$e(t)$ = Instantaneous error

In tuning proportional gain, there are several output results that should be considered. If the proportional gain is set at very high value, it will create an unstable system[13]. Whereas, if the proportional gain is set at very low value, it will come out with another drawback[17]. It is when there are system disturbances, the response likely will be too small to handle the interference. Thus, tuning theory indicate that a huge change in the output will occurred due to high proportional gain[18]. While, a less responsive controller and small output resulted because of small proportional gain as discussed earlier.

3.3.2 Integral Parameter

The integral parameter is yield from the total of instantaneous error over time. An accumulated offset is then generated which must be corrected previously. In order to add the integral parameter to the controller output, integral gain which is Ki needed to be multiplied to the accumulated error[18]. The integral parameter is given by:

$$I_{out} = K_i \int_0^t e(t)dt \tag{3.13}$$

Where,

I_{out} = Output of Integral controller

K_i = Integral gain

$e(t)$ = Instantaneous error

The effect of integral parameter toward the system is that it proportional to magnitude and the duration of the error. Thus, with proper tuning of integral gain, this parameter able to accelerates the response towards set point. Besides, with the existing pure proportional controller that creates residual steady state error, this integral parameter capable to eliminate the problem. In contrast, integral parameter also can generate the present value to overshoot the set point value[18]. This is due to the accumulated errors that it summed previously.

3.4 Proportional (Kp) and Integral (Ki) Gains Tuning

In order to obtained the desired control response, both proportional(Kp) and integral(Ki) gains need to be adjusted to the optimum values. However, for a particular system and application, it have both different behaviour and requirements. Furthermore, the requirement may conflict with each other. Thus, the proposed tuning method is to firstly set the value of Ki to zero. Then, the value of Kp is increasingly adjusted until the response of the system oscillates[19].

Next, the integral gain is then increase until it reach its offset in sufficient time for the process. However, from the previous oscillating system creates by Kp gain, it might create overshoots. Thus, the Kp needed retune until the overshoot eliminated[19]. The table 3.1 below shows the effects when increasing the parameters independently.

Table 3. 1 : PI value setting

Parameter	Kp	Ki
Rise Time	Decrease	Decrease
Overshoot	Increase	Increase
Settling Time	Small Change	Increase
Steady State Error	Decrease	Decrease Significantly
Stability	Degrade	Degrade

3.5 Hysteresis Current Switching Control

The switching sequences of the inverter are important to make sure that BLDC motor will operate smoothly. Thus, hysteresis current control used as the most important part of the torque hysteresis control scheme. By using this technique, the switching states were determined wether it is on or off within a predefined band gap[20] as shown in figure 3.3.

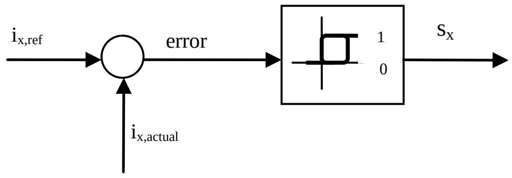

Figure 3. 2 : Hysteresis current control block diagram

The hysteresis current control implements the comparing signals between actual and reference currents in its band gap. When the actual current reach the upper limit, it gives signal 0 and will have signal 1 when it reach lower limit. The operation occurred in continuous.

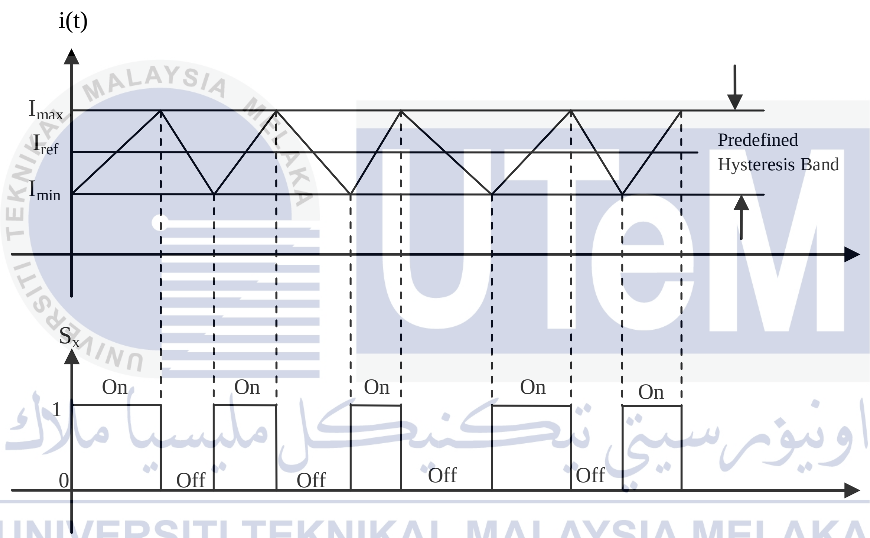

Figure 3. 3 : Hysteresis current control

3.6 Hall Effect Sensor

The voltage source inverter used in the project needed proper switching sequences to ensure that the windings energise at the right time. The sequence is depends on the decoded signals (H_A', H_B', H_C') which are derived from the Hall Effect signals (H_A, H_B, H_C). The derivation has been shown in Table 2.1 in previous Chapter 2. As each of phase reference currents determined by torque and the decode signals, it results the motor currents to follow the same pattern as reference currents.

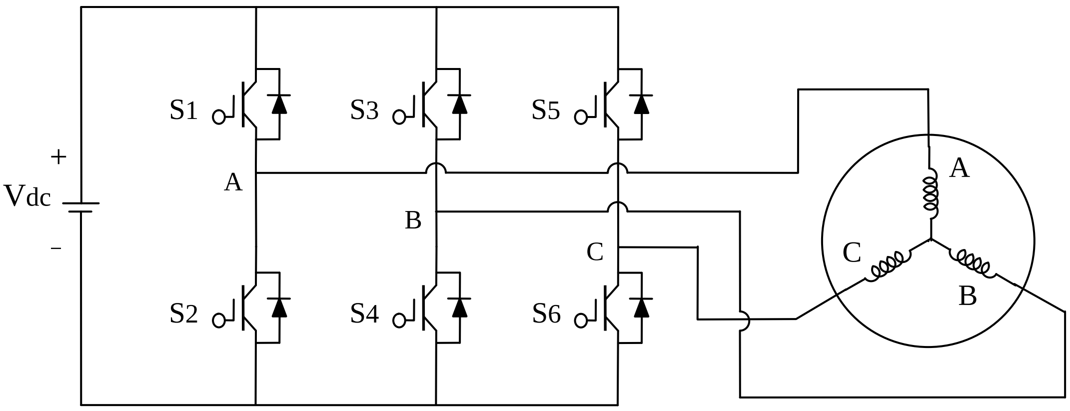

Figure 3. 4 : Voltage source inverter (VSI)

By referring Figure 3.4, the switching states of the VSI are as shown in Table 3.1. The signal 1 indicates that the IGBTs are triggered while 0 indicates it is off. As in Figure 2.3 from Chapter 2, the correct triggering signals to the VSI are important to make sure the proper sequences achieved. As been discussed earlier, in such way, the motor currents have the same shape as decoded signals as given in Table 3.2.

Table 3. 2 : Switching sequence

Switching Sequence	Hall Effect Position Sensor			Switching State					
	H_A	H_B	H_C	S_1	S_2	S_3	S_4	S_5	S_6
1	1	0	1	1	0	0	1	0	0
2	0	0	1	0	0	0	1	1	0
3	0	1	1	0	1	0	0	1	0
4	0	1	0	0	1	1	0	0	0
5	1	1	0	0	0	1	0	0	1
6	1	0	0	1	0	0	0	0	1

Table 3. 3 : Decoded signals and motor phase current

Switching Sequence	Decoded Signals			Motor Phase Currents		
	H_A'	H_B'	H_C'	i_a	i_b	i_c
1	+1	-1	0	+	-	Off
2	0	-1	+1	Off	-	+
3	-1	0	+1	-	Off	+
4	-1	+1	0	-	+	Off
5	0	+1	-1	Off	+	-
6	+1	0	-1	+	Off	-

3.7 Torque Loop Of Experiment And Simulation

In developing both experiment and simulation for BLDC control scheme, there were several procedures conducted. By using the same parameters of actual BLDC motor and simulation BLDC motor, the designing control scheme was started with the experimental. The BLDC motor was connected to iDRIVE which consists complete driver components including dSPACE that used to control the BLDC motor. Besides, the motor also connected to resistance load during the torque test under two conditions of torque. The input or reference torque was step up increasingly to observe the maximum speed that the motor can handle.

The crucial condition for the test is that the motor must able to obtain its maximum speed and at the same time the produce torque still can regulate. Next, as the maximum speed measured and the value of torque that the motor can handle obtained, the torque at the maximum speed will be used as the limiter in the PI speed controller.

3.8 Experimental Speed Loop Test

For speed loop test, the experiments also conducted by using the iDRIVE and dSPACE. As in torque test, the speed test also being monitored with step transition of input. The speed is change from LOW to HIGH which is from 30 rad/s to 60 rad/s. Besides, there also REVERSE -FORWARD test which is from -30 rad/s to 30 rad/s. As discussed, the speed loop is controlled by PI speed controller. Thus, to obtained the perfect performance of speed response, the proper tuning of Kp and Ki is really important.

The criteria of performance that are desired for efficient system is that there should be no overshoot and high dynamic response. Besides, the time parameters such as settling time and rise time also crucial.

3.9 Analytical Approach

3.9.1 Proposed Simulation Algorithm

The proposed simulation for Speed and Torque Control scheme is illustrated as shown in Figure 3.5. The blocks diagram shows the system consists of three control loops that are the actual phase currents feedback, decoded signals from the Hall Effect sensor and actual speed loop. The reference currents were derived from decoded signals as discussed in Chapter 2. The simulation had been generated from the designed control strategy. Figure 3.6 shows the complete simulation designed with respect to setted parameters.

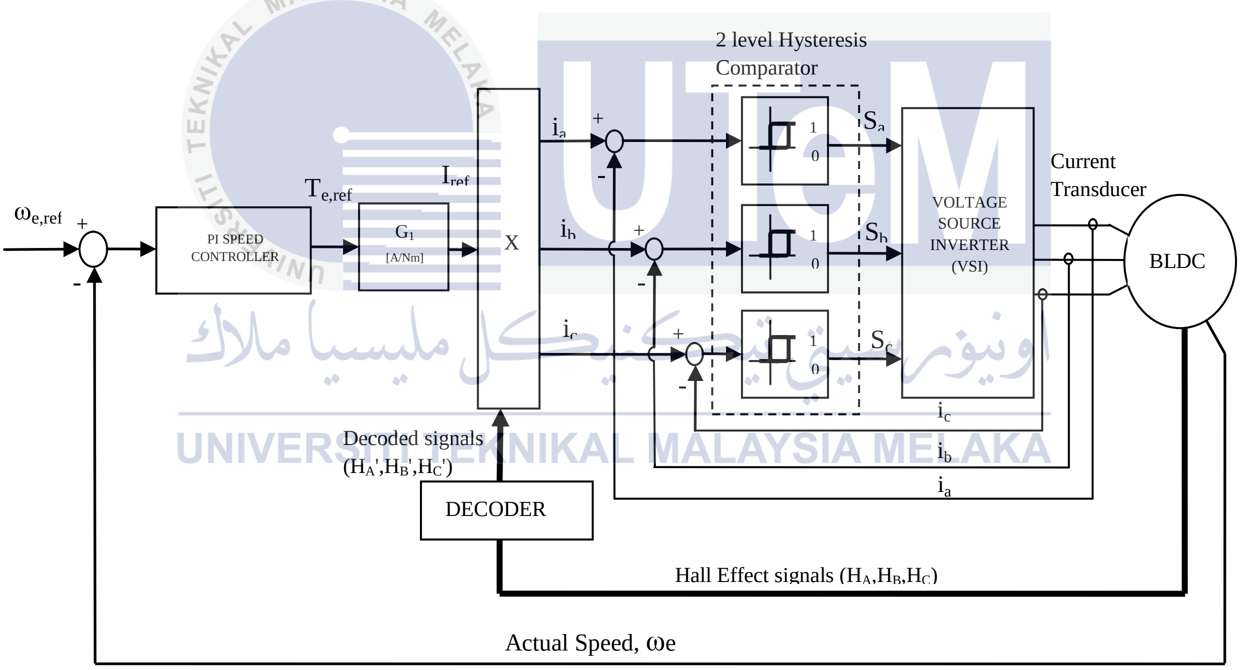

Figure 3. 5 : Structure of Speed Loop of Torque Hysteresis Controller for BLDC motor

3.9.2 Experimental Setup

For the experiment method, it is done using the iDRIVE controller kit in the Power Electronics Laboratory. The iDRIVE was designed with the components that is needed for a motor driver such as the Voltage Source Inverter (VSI), Gate Driver, Decoder, and dSPACE. However, in order to control or communicate the driver and motor, as processor is needed. Thus, dSPACE was used as the interconnection between hardware and the sotfware. Besides, there is also encoder used at the motor shaft to measure the speed of the motor during the operation time.

Next, for measuring all the outputs and feedback outputs, the oscilloscope and Current Transformer (CT) also used in the experiment setup. CT used to measure the actual phase currents to be fed to the controller in order to complete the current loop of the scheme. Whereas, the oscilloscope was used to display the output waveforms. The experimental setup shown in Figure 3.6.

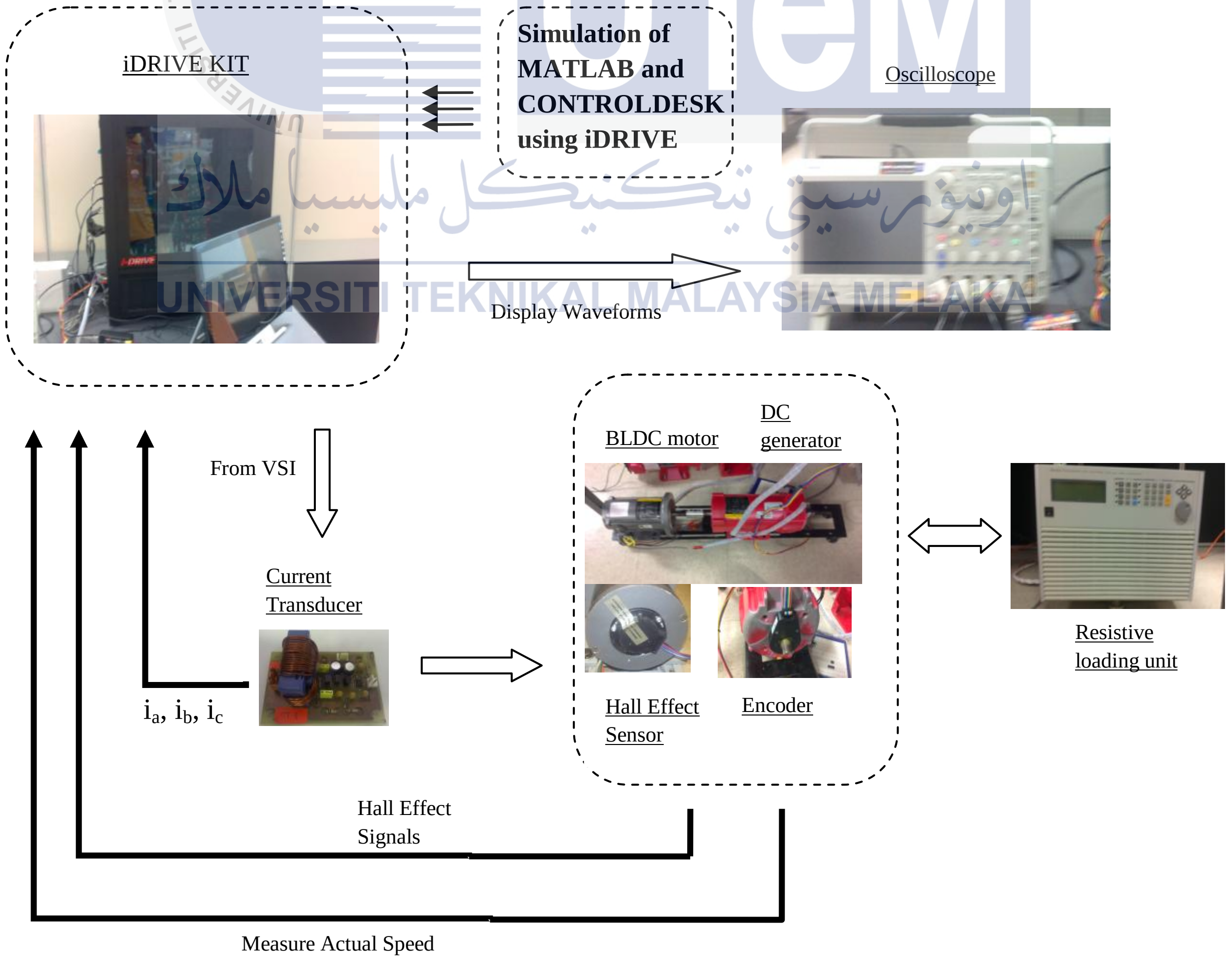

Figure 3. 6 : Experimental set-up

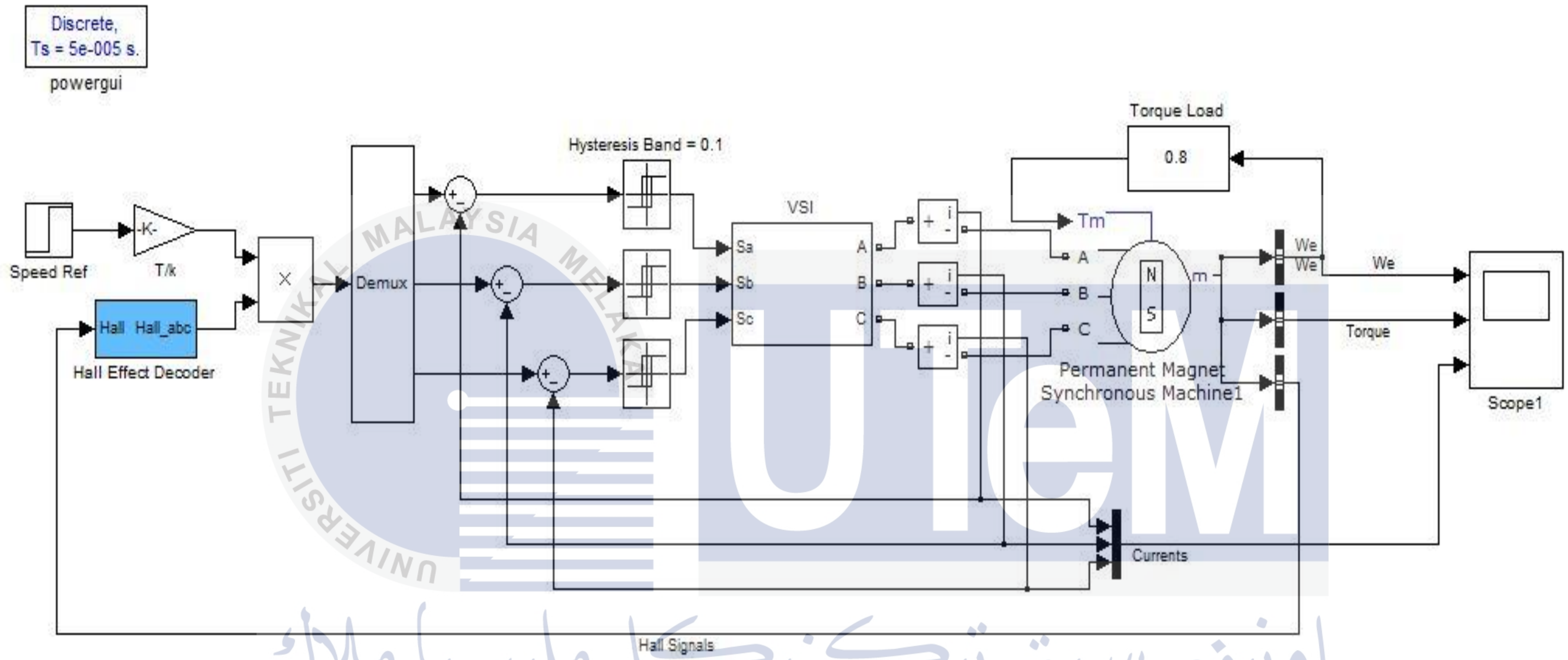

Figure 3. 7 : Simulation Torque Loop of Torque Hysteresis Control for BLDC motor

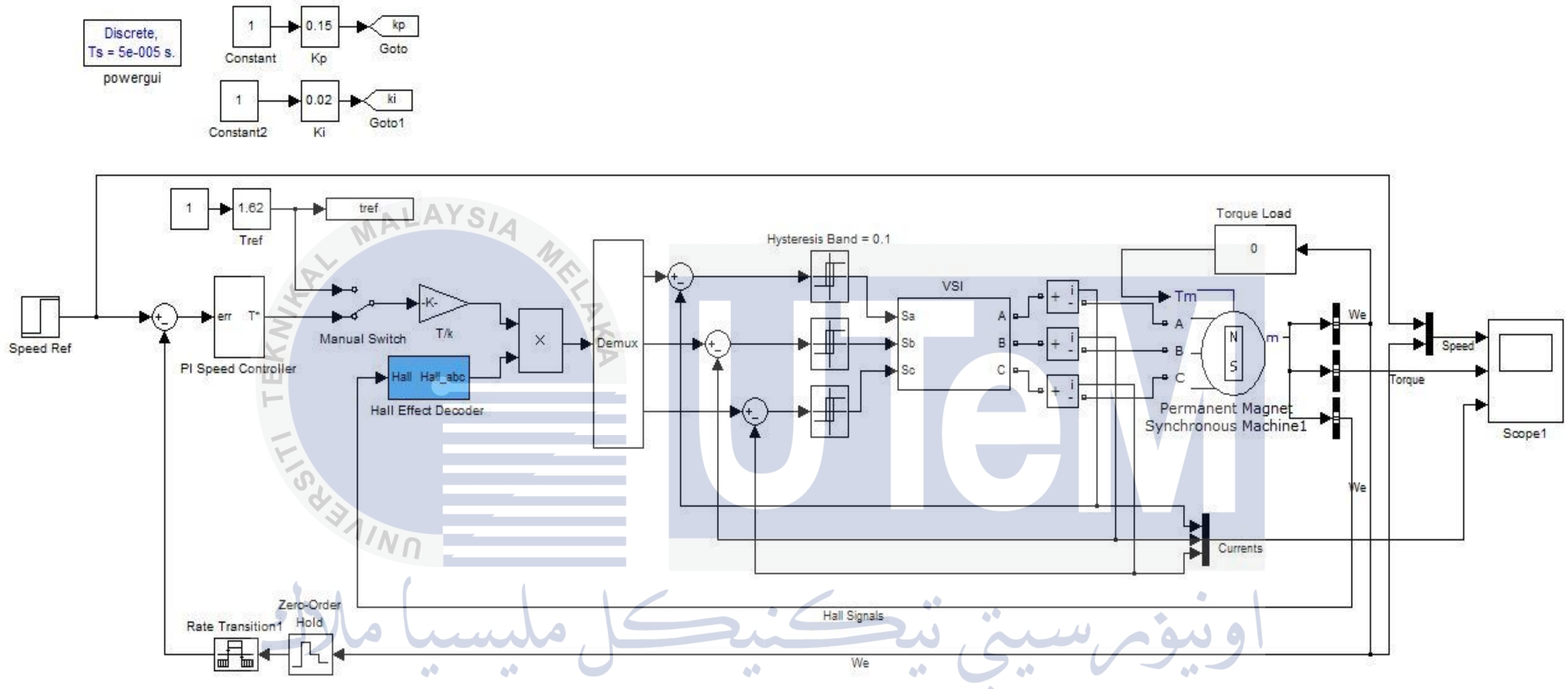

Figure 3. 8 : Simulation Speed Loop of Torque Hysteresis Control for BLDC motor

3.10 Conclusion

Step 1 : Comprehensive investigation on the Torque Hysteresis Control of BLDC motor.

A comprehensive investigation had been done to study and analyse the concepts of Torque Hysteresis Control of BLDC motor. A complete investigation on the literature reviews of the previous related projects, modelling of the motor, and procedures of the project. At this stage, the proposed control strategy must be clearly understood in terms of its theoretically and structure.

Step 2 : Simulation of the proposed control strategy.

The simulation is essential in developing a project. The controlling scheme should be verified using the simulation MATLAB/SIMULINK before conducting the experiment implementation. All the parameters of the control scheme have been tested in this stage. The simulation was troubleshoot until obtain the desired results.

Step 3 : Research of experiment implementation.

After completing the simulation and had been verified of its effectiveness, a research on the potential hardware that will be used for the experimental procedure have been done. All the possible equipments and hardware that can be used on the experimental were take into consideration.

Step 4 : Experiment conduction of Speed and Torque Controls for BLDC machines.

The experiment of the scheme have been done after brief study on the hardware that will be use. This includes the arrangement of the components and the processor's type. Then, after the experiment setup have complete, it have been undergo troubleshoot procedure as in simulation stage to ensure its efficiency. Lastly, the output of experiment was verified with the simulation outputs.

Step 5:Final report writing

The final report writing will be perform after the overall process of the project being conducted. The report will explained in detail about the proposed control strategy of Speed and Torque Controls of BLDC motor.

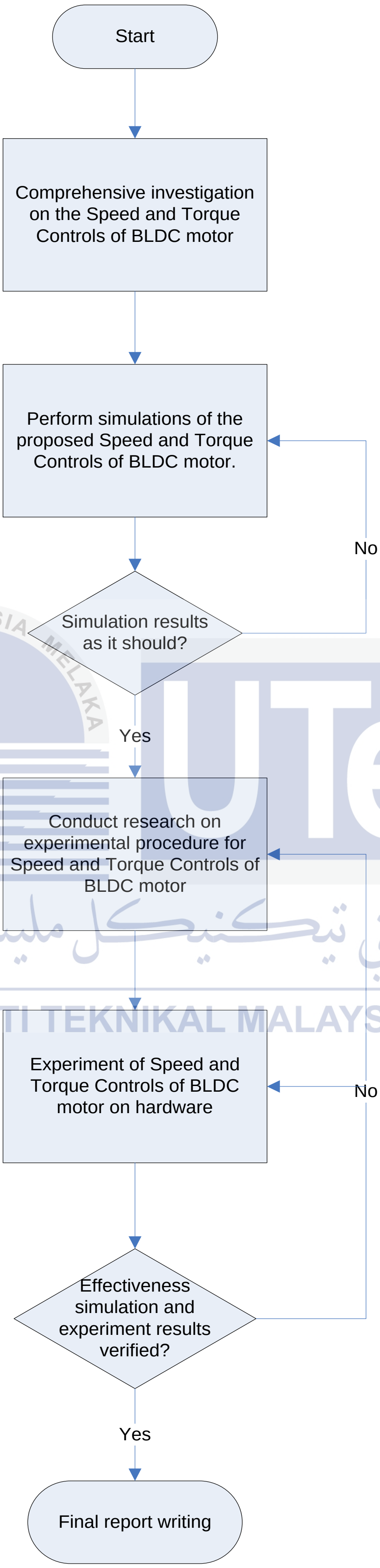

Figure 3. 9 : Flowchart of the project

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This section will discuss about the simulated results. The simulation were performed by using MATLAB/SIMULINK. The process of designing the Speed and Torque Control begin with simulation part by part. After several troubleshoots and the desired results obtained, each of simulation parts were combined to construct the simulation of Torque Hysteresis Control.

As this project include both experiment and simulation, thus it is crucial to ensure both the parameters in both method are same. This is to make sure that the comparisons between both method will be valid. The parameters of the BLDC motor and control are set as in the Table 4.1 and Table 4.2 respectively.

4.2 Parameters Setting

For this section, there were several procedure in order to determine the real parameters of the Brushless DC (BLDC) motor. During the experimental, both of stator phase resistance (Rs) and stator phase inductance (Ls) were obtained by using LCR meter. By adjusting the motor shaft for each 45 degree at certain time, the value of inductance and resistance was taken for a complete 360 degree of the shaft. Both the inductance and resistance values which have 8 readings for each parameters then were calculated for its average value. The obtained parameters then were used in the simulation. The measured parameters were shown in Table 4.1.

Even though the parameters of the BLDC motor was given in its lab sheet, the measurement for the inductance and resistance still need to be done due to tolerance that may occurred. However, for other parameters such Flux Linkage and Moment of Inertia were used with respect to the given values in the lab sheet certificate.

Table 4. 1 : Parameters of BLDC motor

Motor Parameters	Value
Number of pole	4
Stator phase resistance, Rs (Ω)	5.7
Stator phase inductance, Ls (H)	86.8e-3
Flux linkage, ($kgm^2s^{-2}A^{-1}$)	0.110
Moment of inertia, (kgm^2)	0.004713
Friction factor	0.01

Table 4. 2 : Control system parameters

Control System	Value
Step size (fundamental sample time), (s)	50u
Limiting Hysteresis Band,(A)	0.1

4.3 Simulation Results Of Hall Effect Decoded Signals

For the designing the simulation result of Hall Effect decoder, the simulation was constructed to obtain the waveforms as shown in Figure 4.1. The decoder blocks connection was design as shown in Figure 4.2 based on the truth table in Table 4.3 respectively. It then being constructed using simulink blocks in MATLAB.

In designing the Hall Effect decoder, the position of rotor is important to generate the decoded hall signals. Based on the operational of Hall Effect Sensor that have been discussed in Chapter 3 earlier, the decoded hall effect signals possess same shape as reference currents. Then, the reference phase currents were generated depending on the position of rotor which is the decoded signals and the amplitude of reference torque.

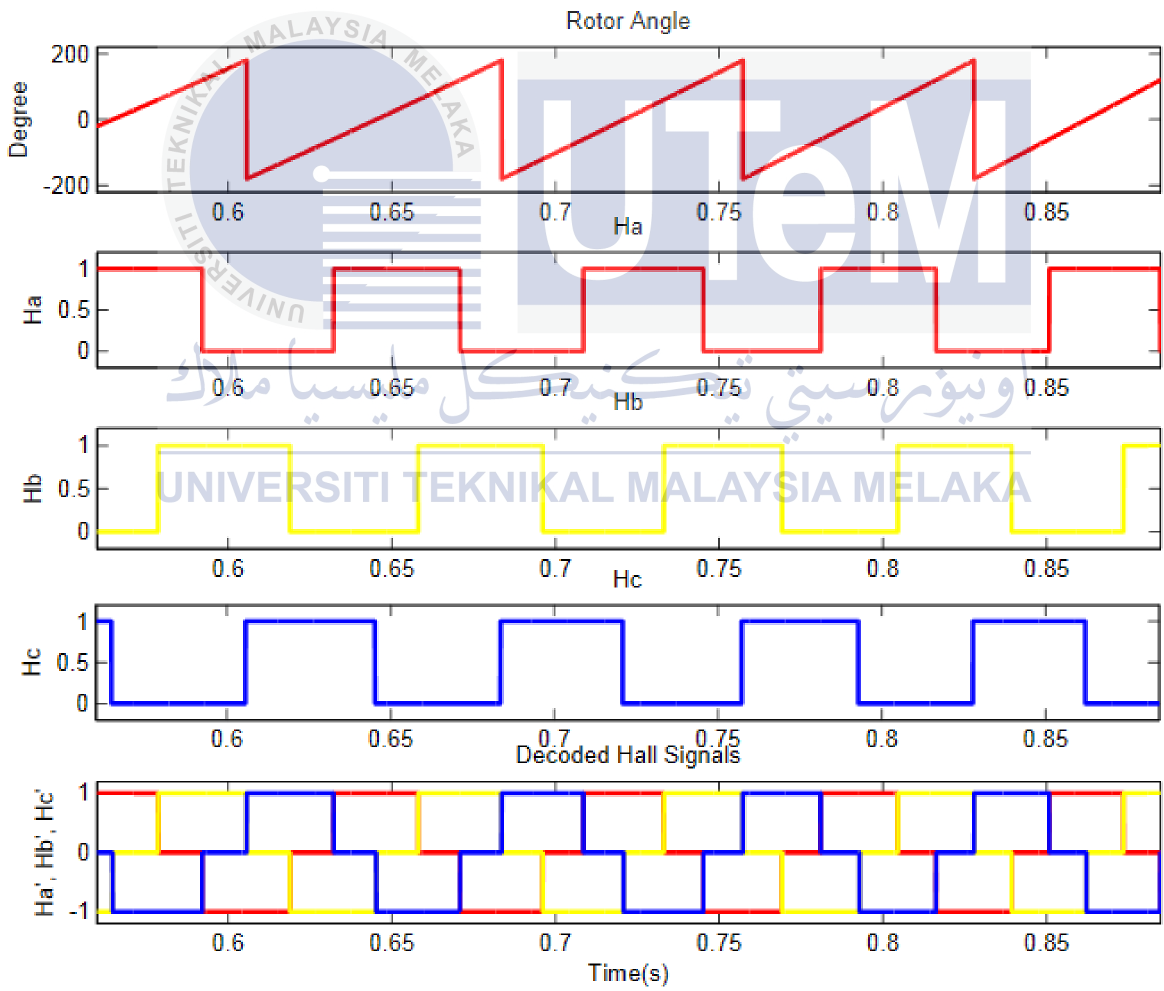

Figure 4. 1 : Waveforms of rotor angle, Hall Effect signals and Decoded Hall Effect signals

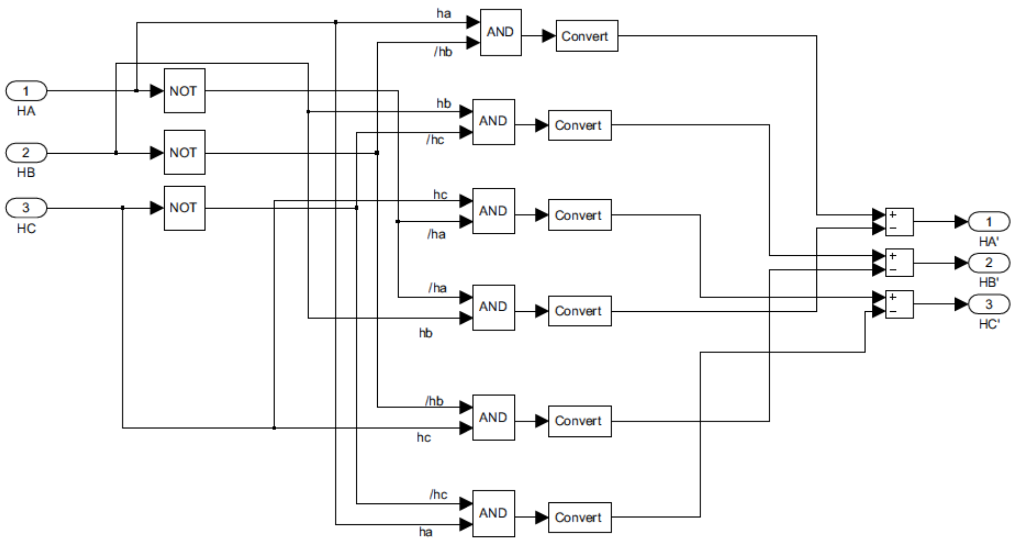

Figure 4. 2 : Subsystems of the decoder

Table 4. 3 : Hall Effect truth table

H_A	H_B	H_C	EMF_A	EMF_B	EMF_C
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+	0	-1
1	0	1	+	-1	0
1	1	0	0	+	-1
1	1	1	0	0	0

In Figure 4.3 and Figure 4.4 shows the Hall Effect signals and its decoded signals respectively. Each of the Hall sensors have distance of 120 degree amongst each of them. Thus, for that signal triggered during detection of the sensors, it will give phase shift of 120 degree between each of the sensors.

Noticed that, for the decoded signals in Figure 4.4, it will produce +, -, as well as 0 signals for each Hall sensors with respect to the truth table in Table 4.3. From this waveform where the reference current will be produced. The DC link current that has been discussed in Chapter 2 under subtopic 2.3.1.3 will be times with the decoded signals to generate the three phase reference currents.

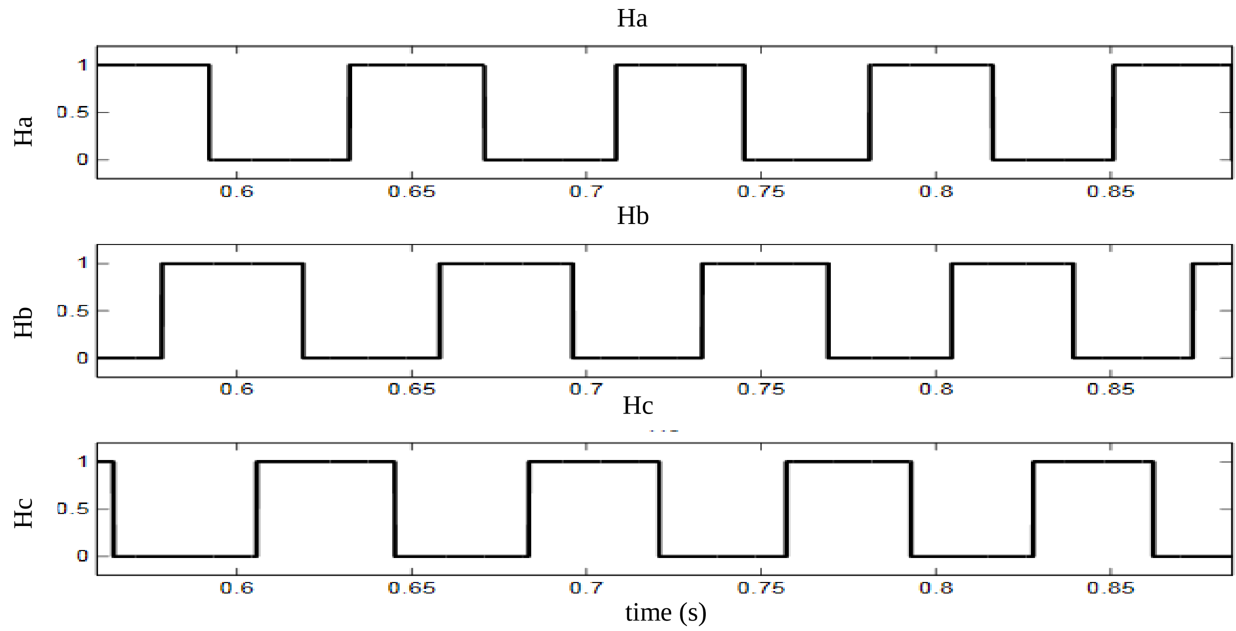

Figure 4. 3 : Hall Effect signals

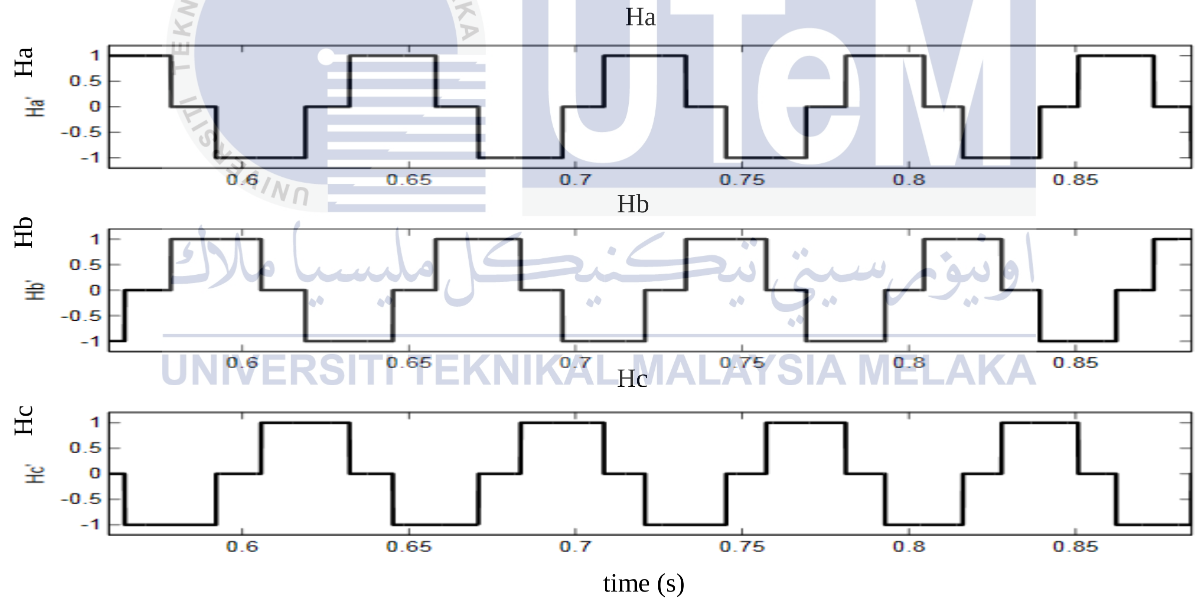

Figure 4. 4 : Decoded Hall Effect signals

4.4 Simulation Of Reference And Actual Currents

Waveform of reference and actual currents shows in Figure 4.5 and Figure 4.6 respectively. As discussed in previous chapter, the production of reference phase currents based on decoded signals and reference current from the desired torque. Equation 2.1 were used to generate the reference current.

$$I_{ref} = \frac{T_{ref}}{k_t} \tag{2.1}$$

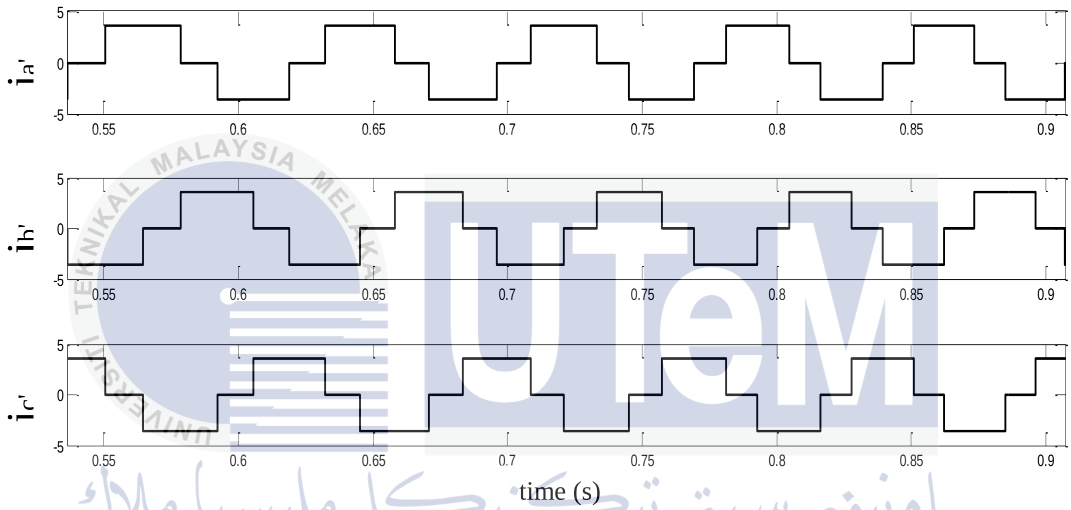

Figure 4. 5 : Waveform of reference currents

For actual currents as shown in Figure 4.6, the waveform of the currents were measured from the motor currents of the BLDC motor simulation. Based on the results, it shows that the actual currents follow the shape or behaviour of reference currents.

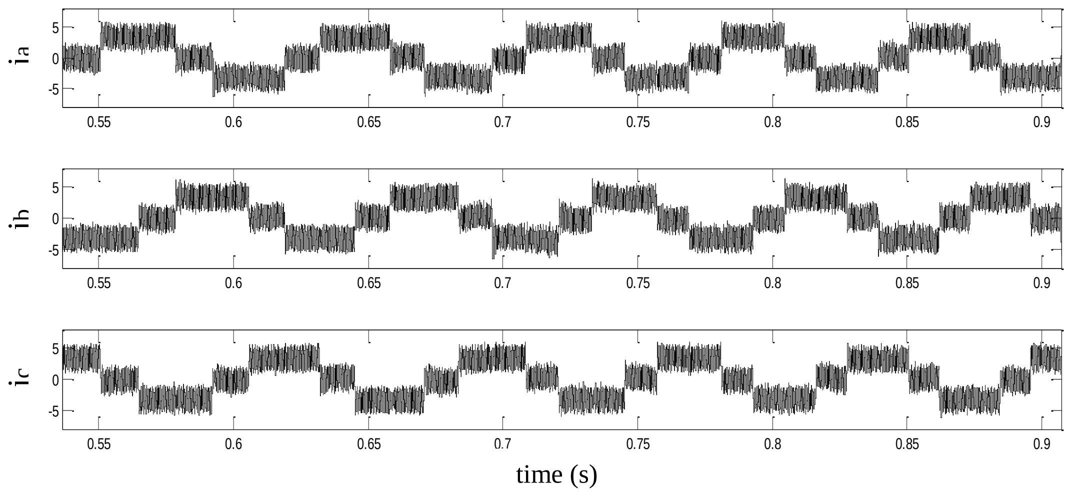

Figure 4. 6 : Waveform of actual currents

4.5 Torque Test

Based on experiment that conducted, the results of the test is as tabulated in Table 4.4 and Table 4.5. The maximum speed of the BLDC motor can obtain is 629 Rpm with under requirement of the torque still regulating is 1.8Nm. The test was carried out with step change of the torque from 50% of maximum which is 0.9Nm to the 1.8Nm. This method was done to measure the capability of motor to response for a sudden step up change of torque.

Table 4. 4 : Load parameters

Parameters	Value
Resistance Load, RL	15 Ω
Peak Current, Ip	5 A

Table 4. 5 : Torque test results

Parameters	Torque = 0.9Nm	Torque = 1.8Nm
Speed, (ω)	241 rpm	629 rpm
Voltage, (V)	5.4 V	16.02 V
Current, (I)	0.28 A	1.08 A
Power, (P)	1.48 W	17.43 W

Based on the experimental and simulation result as shown in Figure 4.7 and Figure 4.8 respectively, both shows the step change of torque from 0.9Nm to 1.8Nm with steadily regulating torque. Besides, during the operation, the phase currents and current error also shows a good criteria. From the experiment torque loop, the bandwidth of the torque was set at 1.8Nm to -1.8Nm.

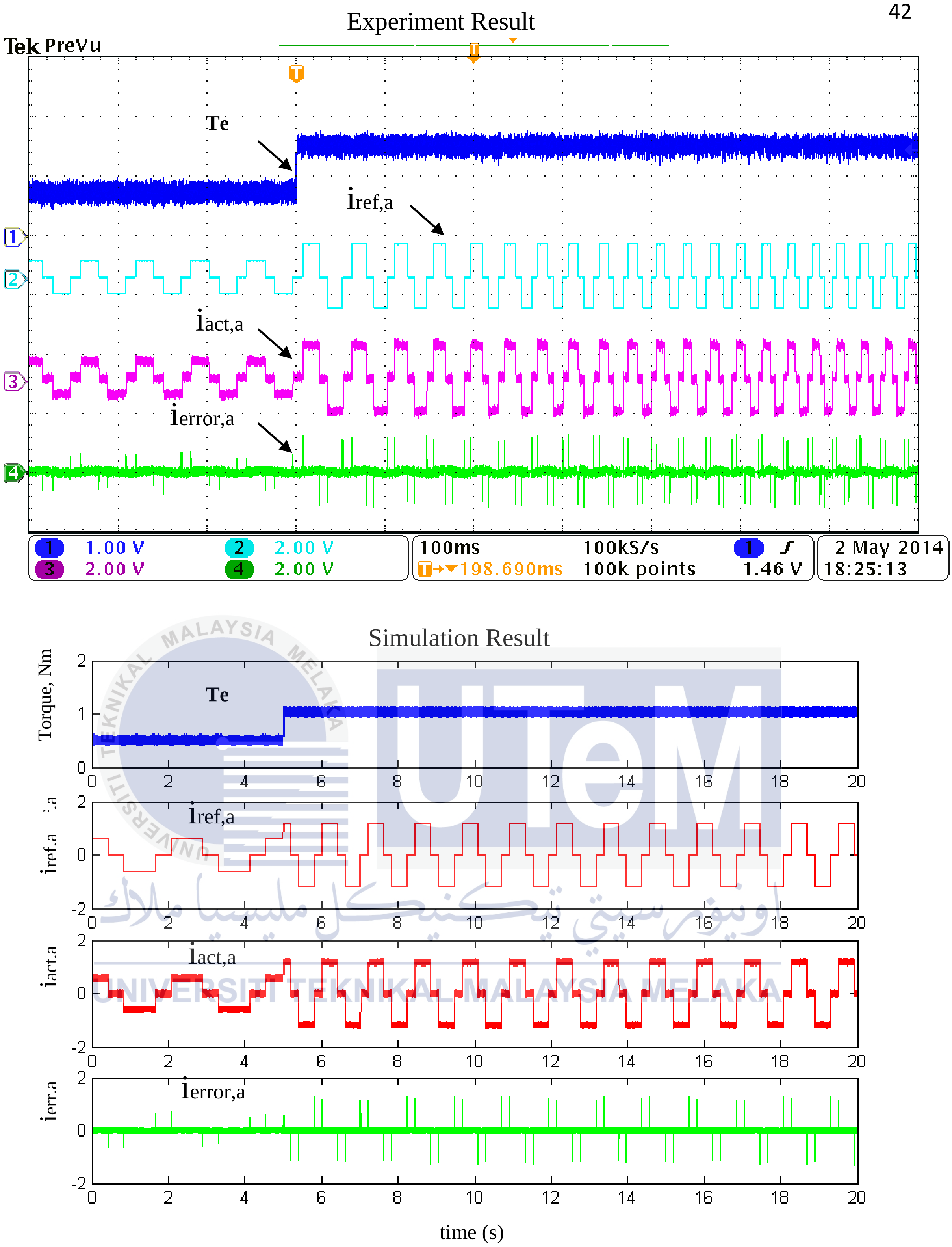

Figure 4. 7 : Comparison between experiment and simulation results

4.6 Low-High Speed and Reverse-Forward Speed

For the speed, torque, and phase currents results, both of the experiment and simulation results were generated with respect to same parameters. Based on the speed from low to high as shown in Figure 4.8, both results from simulation and experiment gives out same output with respect to the amplitudes and also the time response for each of the output parameters. However, due to mechanical error that may occurred due to the uneven coupler of the motor, the PI speed controller needed a slightly adjustment in simulation mode. The parameters shown in Table 4.6.

Then, for the phase currents for both operations, the output parameters from speeds up to currents are related to each other. It can be seen in both Figure 4.8 and Figure 4.9 that when the speed increased or there is a speed transition, the torque also will be increase until the speed reached the steady state condition and the torque also follow the same behaviour. Noticed that, during the torque exchange to higher value, the currents also shows high value. This is because in DC machines current is directly proportional to torque.

Table 4. 6 : PI controller gains set up for Low-High operation

Parameters	Proportional Gain, Kp	Integral Gain, Ki
Simulation	0.15	0.12
Experiment	0.15	0.02

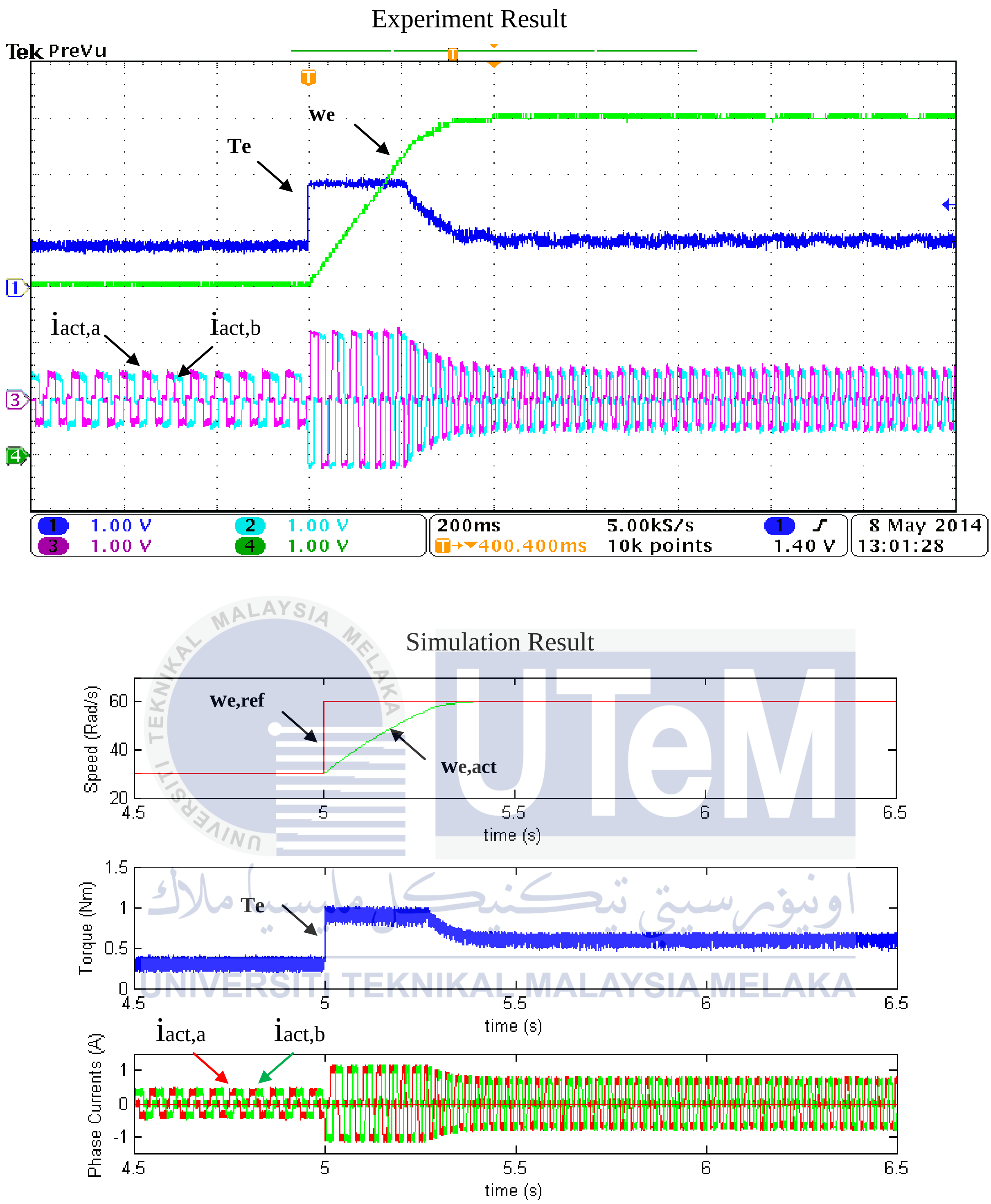

Figure 4. 8 : Comparison of experiment and simulation results for transition speed from 30 rad/s to 60 rad/s

Next, for reverse-forward operation, the current shows that during the transition between reverse to forward there are changes in the phase rotation. From the explained operation of BLDC motor discussed earlier in Chapter 2, the motor operate in three phase system. For normal forward operation, the rotation phase of the current is A-B-C. While for reverse, the rotation will be backward which is C-B-A. Thus, when involving different rotation of motor, the rotation of phase current also will change. Based on Figure 4.9, during reverse operation, the current happens to be phase B leading phase A. While, after the transition of rotation of motor, the phase current A leading phase current B.

However, as said earlier, the minor adjustment is on the integral gain for both low-high and reverse-forward operation. For the experiment, the Ki gain needed to be higher than Ki in simulation. Whereas, the Kp gain still remain same for both experiment and simulation. This could be due to the interference on the hardware that has effect the experimental results. Yet, this results have proved for both operations that the designed control scheme for BLDC can be reliable. The parameters of PI controller shown in Table 4.7.

Table 4. 7 : PI controller gains set up for Reverse-Forward operation

Parameters	Proportional Gain, Kp	Integral Gain, Ki
Simulation	0.17	0.12
Experiment	0.17	0.14

Experiment Result

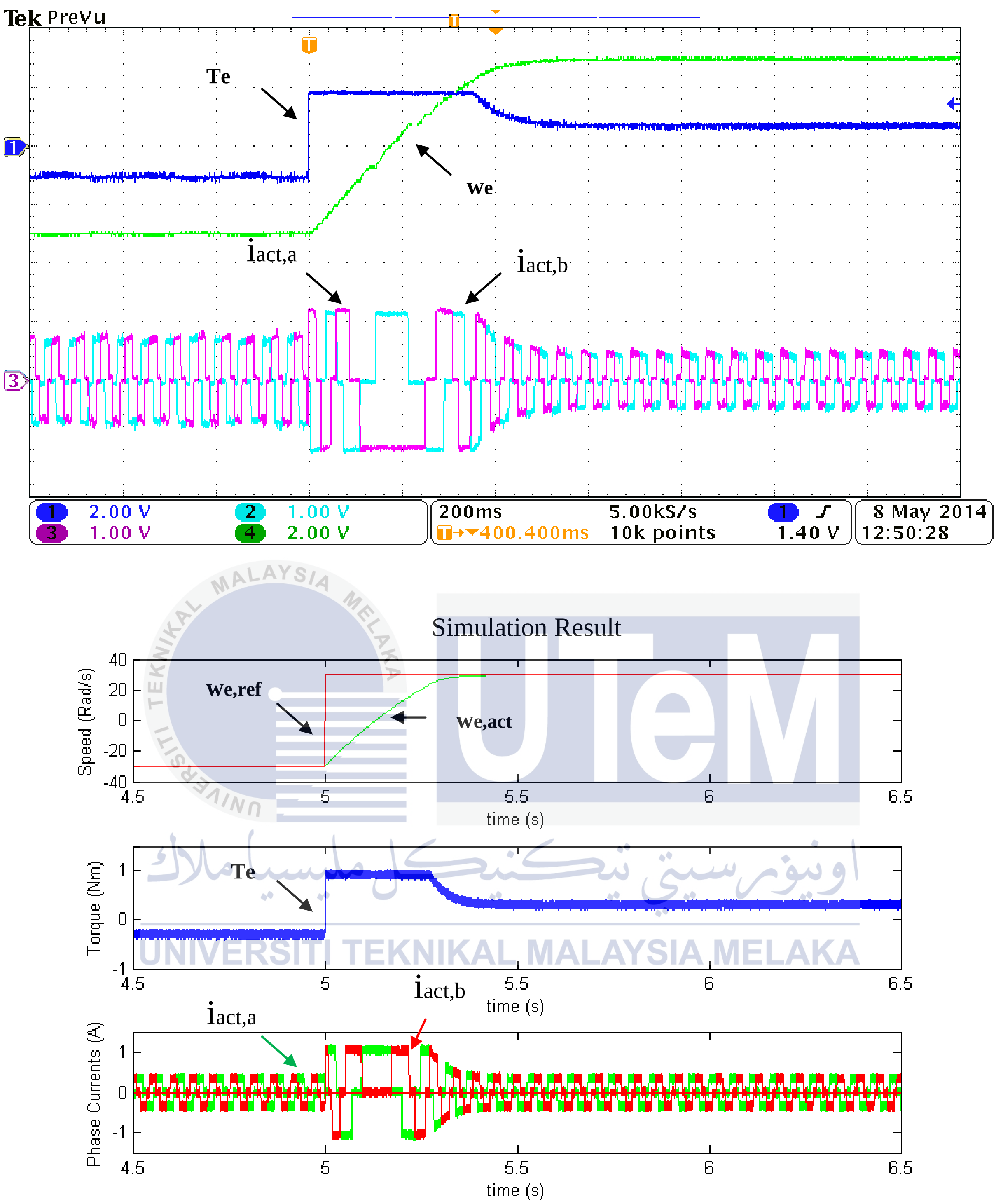

Figure 4. 9 : Comparison of experiment and simulation results for speed transition from -30 rad/s to 30 rad/s (Reverse Forward)

4.7 Overshoot and Low Dynamic Response

For low dynamic response and overshoot condition, the output waveforms are shown in Figure 4.10 and Figure 4.11 respectively. In low dynamic response condition, the Kp gain were reduce to 20 % from set Kp parameter. The original parameter is 0.15. Thus, the current Kp gain is 0.03 and the Ki gain were fixed as the original value of the system. From the Figure 4.10, the dynamic response is low and this verified the theoretically of proportional controller as discussed in Chapter 2. This resulted from the too small value of Kp. Besides, the torque output seems to be too slow for it to reach the steady state.

Next, for overshoot condition, with the previous value of Kp which 0.15 and increment of Ki to a value of 0.4, the operation runs in experimental method. From the Figure 4.11, it shows that with a too high value of integral gain, it will gives an overshoot system. From the experimental, the proper selection of both gains is important as in the theoretical of PI speed controller. The parameters for both overshoot and low dynamic response shown in Table 4.8.

Table 4. 8 : Parameters of PI controller for overshoot and low dynamic response

Parameters	Proportional Gain, Kp	Integral Gain, Ki
Ideal Operation	0.15	0.02
Overshoot Operation	0.15	0.4
Low Dynamic Response	0.03	0.02

Experiment Result

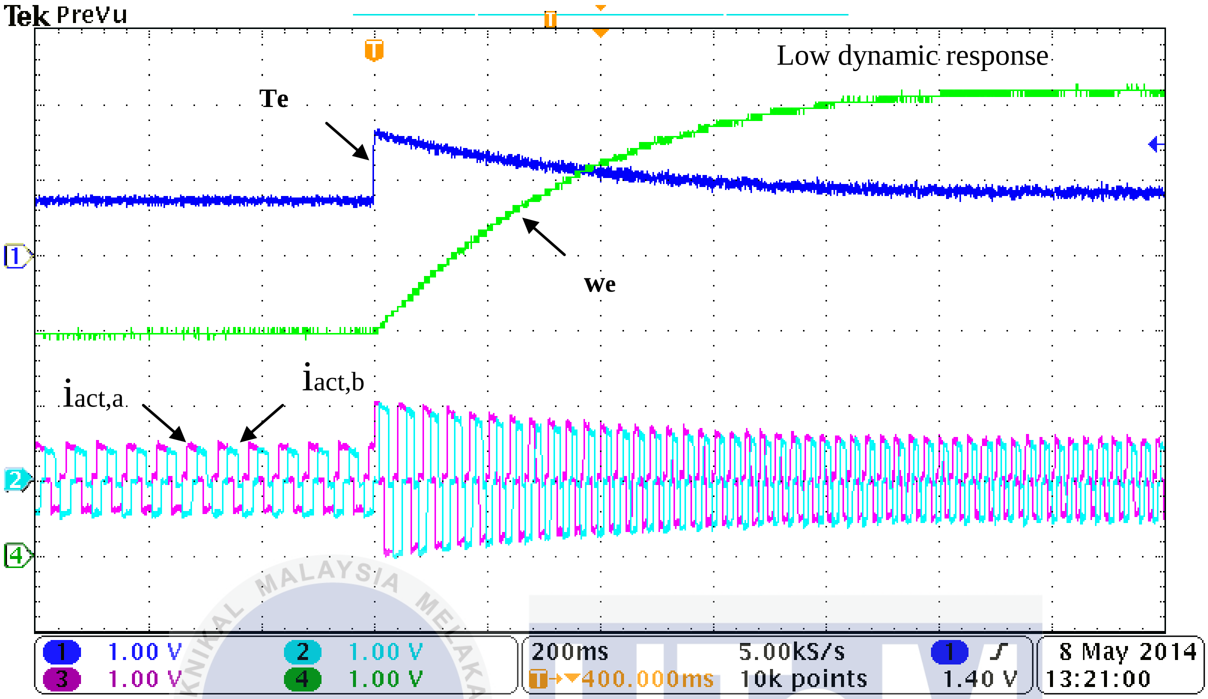

Figure 4. 10 : Waveforms of speed, torque and phase currents of low dynamic response

Experiment Result

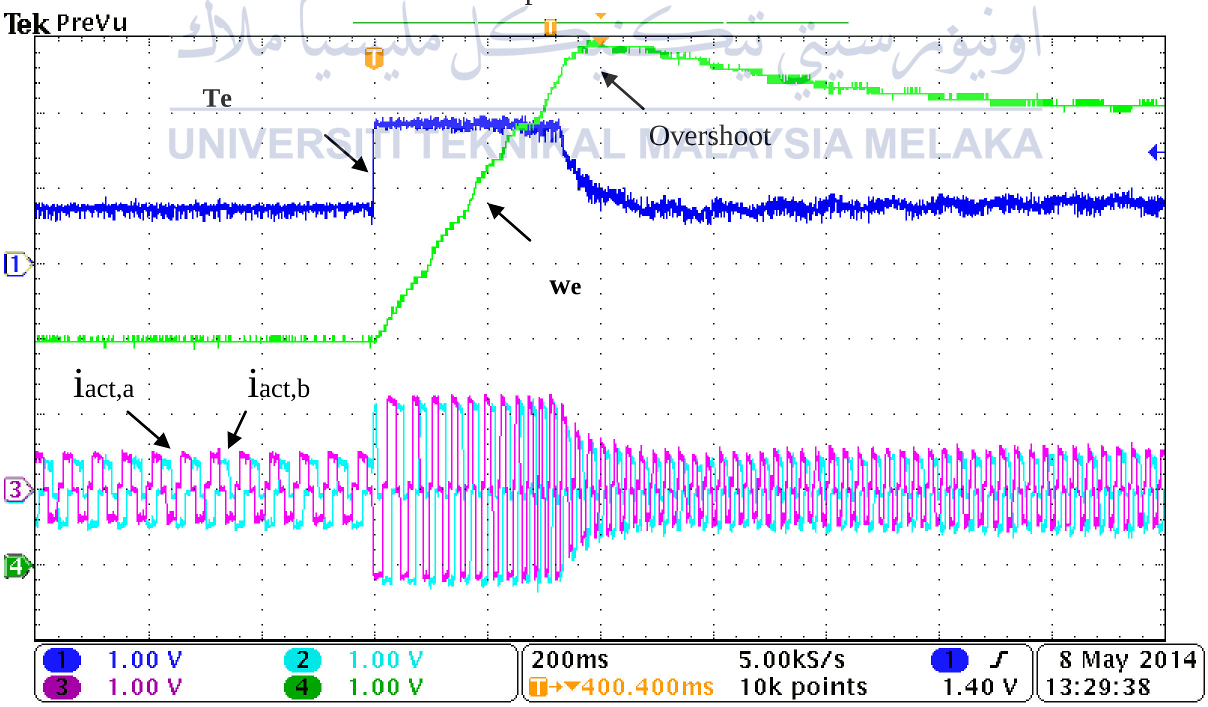

Figure 4. 11 : Waveforms of speed, torque and phase currents of overshoot

CHAPTER 5

CONCLUSION

From the proposed project, the implementation of Speed and Torque Controls was used for BLDC motor drive. This report have discussed about the theoretical and strategy used to meets the objectives. Based on the simulation and experiment of the control scheme in FYP 2, it proved that the proposed control scheme of BLDC creates an efficient controller.

However, there are several external factor that should be considered that may affect the controlling scheme. One of the factor is that the mechanical error which is the uneven coupler that connects between BLDC and DC generator, if there is slightly unbalance mechanical connection, it will effects the performance of the BLDC motor. Besides, as been proposed and discussed, a proper selection of PI speed controller gains also crucial as it controls the behaviour of the system in terms of dynamic response, steady state error, and robustness of the system. With improper of gains settings, it will effect all the system and will creates the ineffective control scheme.

Despite of that, as the results obtained in the project, this conventional PI controller still possess disadvantages. One of them is that the system is not robust as it needs manually selection of PI controller gains. Thus, if there is flaw during the motor operation, it cannot improve the system by itself.

RECOMMENDATION

Based on the project conducted, the proposed control scheme which is the Speed and Torque Controls of BLDC motor have proved of its liabilities and efficiency in controlling BLDC motor. However, the conventional PI controller still have disadvantages in its mechanism. Thus, based on the literature reviews on the other type of controllers that exist for controlling machines, there are several improvement that can be made to improve the performance of the BLDC motor. Amongst of the controller are Sliding Mode Control and Fuzzy Logic Control that have better controlling mechanism to the motor. Based on the mechanism, both of the controllers able to exhibit the fullest and excellent performance of BLDC motor in terms of robustness and dynamic response.

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APPENDIX A : GANTT CHART OF THE PROPOSED PROJECT

The gantt chart provided is the flow of the project that have ensure the completion of this thesis. The progress of the project is distributed monthly started on November 2013 until the final writing report on May 2014. The highlighted region in the gantt chart shows the period of time on which each section of the project should be completed on.

Table 7. 1 : Gantt chart of the project

Milestone	Year	2013				2014				
	Task	9	10	11	12	1	2	3	4	5
1	Investigation on Speed Loop of THC for BLDC motor									
2	Simulation of Speed Loop of THC for BLDC motor									
3	Verification of the simulation results									
4	Progress report writing									
5	Research on experimental implementation									
6	Experiment arrangement and execution									
7	Comparisons and verification of experiment and simulation results									
8	Final report writing									