IMPLEMENTATION OF TORQUE HYSTERESIS CONTROLLER (THC) FOR BLDC MOTOR UTILIZING DSPACE 1104

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“ I hereby declare that I have read through this report entitle “*Implementation of Torque Hysteresis Controller (THC) for BLDC Motor Utilizing DSpace 1104*” and found that it complies the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering”

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A report submitted in partial fulfilment of the requirements for the degree of Bachelor of Electrical Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

I declare that this report entitle "*Implementation of Torque Hysteresis Controller (THC) for BLDC Motor Utilizing DSpace 1104*" 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.

Signature : ....

Name : NURFARAH BINTI ROSMAN

Date : ....

DEDICATION

To my beloved mother and father

My beloved siblings

My supervisor and lecturers

My fellow friends

For their moral support and encouragement through my journey of education

ACKNOWLEDGEMENT

First and foremost, I would like to express my gratitude to the Almighty Allah SWT for His willing in giving me the strength to complete my Final Year Project 1.

I would love to express my profound gratitude to my supervisor, Dr. Auzani bin Jidin for his exemplary guidance in supervising me throughout the course of this project.

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Last but not least, thanks to my family for their moral support and encouragement in completing this project.

ABSTRACT

This project presents the implementation of Torque Hysteresis Controller of BLDC Motor (BLDC) drive using a dSPACE 1104. BLDC motor is well-known and has been widely used in the industrial area due to its high speed and power density capabilities. Electronic commutation is by far more favourable compared to the conventional method, which uses brushes and commutators, that wear and tear by time. However, a precise controller is required in order to control the switches prior to commutation process. Over the past years, Torque Hysteresis Controller (THC) method for induction motor drives received lots of attention from researchers, and motor drive industries. THC of BLDC combines a simple control method and a demanding motor to complete a better drives system. THC method is known to have a simple structure without having complex calculations thus offers a fast response and a good dynamic performance. The previous work which is the Voltage Controlled of BLDC motor contributes a very high current during the start-up. A mathematical modeling which is created using Matlab simulation on the motor drive for Brushless DC Motor is presented along with a complete model of the THC system for BLDC motor using Simulink Block. The model is described briefly to give a better understanding on the whole system. Finally, the simulation and are shown to validate the performance of THC of BLDC motor with improvements of the problem highlighted.

ABSTRAK

Projek ini membentangkan pelaksanaan Pengawal Hysteresis Torque BLDC Motor (BLDC) dengan menggunakan dSPACE 1104. Motor BLDC terkenal dan telah digunakan secara meluas di kawasan perindustrian kerana keupayaan kelajuan tinggi dan ketumpatan kuasa. Pergantungan elektronik jauh lebih menguntungkan berbanding dengan kaedah konvensional, dimana penggunaan berus dan komutator akan lusuh mengikut masa. Walau bagaimanapun, pengawal tepat diperlukan untuk mengawal suis sebelum proses penggantian. Sepanjang tahun yang lalu, kaedah Kawalan Tork Hysteresis (THC) untuk pemacu motor induksi menerima banyak perhatian daripada penyelidik dan industri pemacu motor. THC BLDC menggabungkan kaedah kawalan mudah dan motor untuk melengkapkan sistem pemacu yang lebih baik. Kaedah THC diketahui mempunyai struktur mudah tanpa pengiraan yang kompleks dengan itu menawarkan tindak balas yang cepat dan prestasi dinamik yang baik. Mengikut projek yang pernah dijalankan sebelum ini iaitu Kawalan Voltan bagi motor BLDC, kaedah ini menyumbang arus yang sangat tinggi semasa permulaan. Pemodelan matematik yang dibuat menggunakan simulasi Matlab pada pemacu motor untuk Brushless DC Motor dibentangkan bersama model lengkap sistem THC untuk BLDC menggunakan blok Simulink. Model digambarkan secara ringkas untuk memberi pemahaman yang lebih baik ke seluruh sistem. Akhir sekali, simulasi dan ditunjukkan untuk mengesahkan prestasi THC motor BLDC dengan penambahbaikan masalah yang diketengahkan.

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LIST OF ABBREVIATIONS

BLDC	BRUSHLESS DIRECT CURRENT
DC	DIRECT CURRENT
AC	ALTERNATING CURRENT
THC	TORQUE HYSTERESIS CONTROLLER
DTC	DIRECT TORQUE CONTROL
IGBT	INSULATED GATE BIPOLAR TRANSISTOR
VSI	VOLTAGE SOURCE INVERTER
CSI	CURRENT SOURCE INVERTER
DSC	DIRECT SELF CONTROL
PMSM	PERMANENT MAGNET SYNCHRONOUS MOTOR
GTO	GATE TURN OFF
ADC	ANALOG DIGITAL CONVERTER
FPGA	FIELD PROGRAMMABLE GATE ARRAY
EMF	ELECTROMOTIVE FORCE

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Conventional dc motors are highly efficient and their characteristic makes it reliable for use in many applications. However, the only drawback is that it uses commutator and brushes that require frequent maintenance and cannot be performed at dirty and explosive environment and at very high speed operating conditions. Maintenance-free motor can be developed by replacing the functions of commutator and brushes by solid-state switches, and these types of motors are now known as brushless dc motors. Brushless dc (BLDC) motors are, in fact, a type of permanent magnet synchronous motors (PMSM). It is driven by dc voltage, and the current commutation are done by solid-state switches.

BLDC motor has advantages of longer lifespan, faster torque response and capability of high speeds drive in comparison with DC motor. BLDC motor implements the basic operating principles of DC motor operation but with a difference by placing the permanent magnet in the rotor and coils in the stator. The coil windings are electrically separate from each other, which allow it to be turn on and off in a sequence that creates a rotating magnetic field. The rotor position needs to be determined so that excitation of the stator field always leads the permanent magnet field to produce torque. The commutation instants are determined by the rotor position, and the position of the rotor is detected either by position sensors or by sensorless techniques. The signals from Hall Effect sensors that usually used in BLDC motor need to be decoded to determine the shaft and energize the appropriate stator windings.

The power electronic converter is necessary to operate the BLDC machine. The converter is three phases DC to AC converter, and it consists of six solid-state semiconductor switches. Mosfets and IGBT are the most common types of switches used. In lower power application, mosfets are preferred over IGBT. The power electronic inverter must be capable of applying positive, negative and zero voltage across the motor phase terminals. Each drive phase consists of one motor terminal driven high, one motor terminal driven low, and one motor terminal floating.

1.2 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 motor 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 improvements in order to improve the speed control performance of the BLDC machines to its fullest. Based on the previous control algorithm which is the Voltage Controlled of BLDC motor, the main problem of that method is high current during start-up and the current measurement cannot be controlled. Thus, the Torque Hysteresis Controller of BLDC motor is introduce due to its advantages to overcome the problem on previous work.

1.3 Problem Statement

In the last two decade, several variations of BLDC drives have been proposed and one of them is a Voltage Controlled of BLDC motor. However, this existing works have their constraint that need to be overcome. The main problem for Voltage Controlled of BLDC motor is it produce very large current during start-up since it does not provide current limitation. If a large demand is being injected which means increase the speed, the torque will become larger due to no current control obtained. Plus, they have no current loop since no current sensor is being used. This is because their feedback is based on Hall Effect Sensor only.

1.4 Objective

The aims of this project are:

1. To limit the current by established current control loop.
2. To operate the proposed THC in BLDC motor.
3. To verify the effectiveness of proposed THC drives through simulation and experimental results.

1.5 Scope of Project

This project are mainly focuses on study of Torque Hysteresis Controller strategy for BLDC motor. Other than that, the THC of BLDC motor will be implemented using Dspace 1104. Last but not least, the focus is on the construction of the hardware for THC of BLDC motor.

1.6 Report Outlines

First and foremost, this report consists of 5 chapters that starts with Chapter 1 and contains the brief explanation about the proposed technique in the project background and motivation which is the implementation of Torque Hysteresis Controller (THC) for BLDC motor utilizing DSpace 1104. The problem statement is being stated in this chapter and supported by the objective and scope of project. This is the most important part to ensure the vision of the project is clearly understood.

The Chapter 2 presents the literature review which relates with the previous existing works.

Next, for Chapter 3, the methodology of the project was clearly described. This is to ensure that the process of conducting the project are in the right track and follow the sequence.

After that, the Chapter 4 shows the discussion in overall results of the simulation using Simulink in MATLAB software regarding the comparison in details between previous existing work which is the Voltage Controlled of BLDC motor and the proposed technique which is the Torque Hysteresis Controller of BLDC motor. The results obtained will indicates whether the proposed technique has meets the desired output of the proposed control scheme or not.

Last but not least, Chapter 5 explains the conclusion of the research project whether it achieves the desired objective and able to solve the problem stated or not. As for that, some of the recommendation for a better control scheme are also being proposed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In open loop control system, the deviation in output direct current (DC) voltage have a problem commonly when the load is variable. However, this problem can be solved when a closed loop control is used as it will get a fixed output. In the close loop control, the current signal is matched with the reference current to decline the error in output so that the desired output can be obtained. [1]

2.2 Construction of Brushless DC Motor

Brushless Direct Current (BLDC) motor is the synchronous motor with combination of two conventional motor which is the installation for the stall torque capability of a conventional brush-type direct current (DC) motor and the high speed operation capability associated with an alternating current (AC) induction or reluctance motor drives.

The brushless DC drive system has better performances than the brushed DC drive system. The absence of brush gear and commutator increase the operation speed rather than conventional DC machines which leads to reductions in weight and volume. The elimination of commutator segments precludes the problem of segment oxidation. The lack of brushes eliminates certain types of radio frequency interference. The use of permanent magnet rotor leads to the elimination of rotor copper losses which improves the thermal characteristics. The development of high energy permanent magnet materials allows the rotor diameter to be smaller compared to a conventional brush-type motor. This yields lower rotor inertia and faster the acceleration [2].

An induction motor has an excellent properties for high speed. However, they have relatively low power factor and efficiency when operates at lower speed due to the heavy weight and thus, it becomes costly. Unlike induction motor, synchronous motor such as BLDC motor is particularly compatible for low speed drives since its efficiency is high. Although it is more complex to build, their weight and cost are often less than induction motor with equal power and speed. A synchronous motor can improve the power factor of a plant while carrying its rated load. Plus, its starting torque is greater than an induction motor due to the high resistance of the squirrel-cage winding without affecting the speed and efficiency at synchronous speed [3].

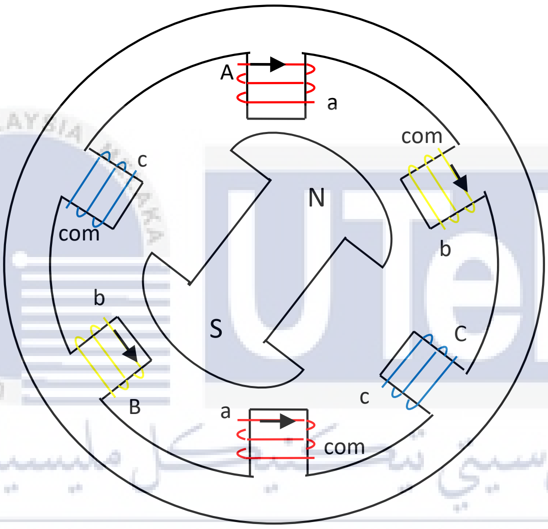


Figure 2.2: Construction of BLDC Motor.

2.3 Operation of Brushless DC Motor with Hall Effect Sensor

The recent trend has been used the brushless dc motor in order to make the operation more reliable, more efficient and less noisy. If the same power output is being applied, this type of motor are lighter compared to Brushed DC motor as the brushes in conventional DC motors wear out over time and sometimes leads to spark. This is the main reason Brush DC motors are not compatible to be used for operations that demand longer lifespan and reliability.

An electronic controller is used to determine which and when the stator coils to be energized so that the rotor will get a continuous rotation. A sensor determines the position of the rotor and the controller decides which coils to be energized. In this case, a Hall Effect sensor is mostly used for the motor. The rotor of the BLDC motor is the permanent magnet and the stators are winded with coils. When a DC power supply is being applied to the coil, the coil will energized and magnetized. Thus, it becomes an electromagnet. The operation of the BLDC is based on the simple force interaction between the permanent magnet and the electromagnet. For this condition, when the coil A is energized, its opposite poles on the rotor and stator will attracted to each other. Since the rotor now nears to coil A, then coil B is energized. When the rotor is near to coil B, coil C is energized. After that, coil A is energized with the opposite polarity and this process is repeated along with the continuous rotation of the rotor.

However, even though this motor works, it has one drawback because only one coil is energized at a time. The two dead coils greatly reduce the output power of the motor. In order to overcome this problem, simply energize the coil behind the first coil when it is in the position that pulls the rotor so that it will push the rotor. For instance, the same polarity current is passed through the second coil. The combined effect produces more torque and output power from the motor. Plus, the combined force also make certain the BLDC motor consists of constant torque nature. As for that, two coils need to be energized separately but the process can be simplified by making a small modification to the stator coil. This process can be done by connecting one free end of the coils together. Therefore, when the power is applied between coils A and B, the current flow through the coil is like the separately energized state.

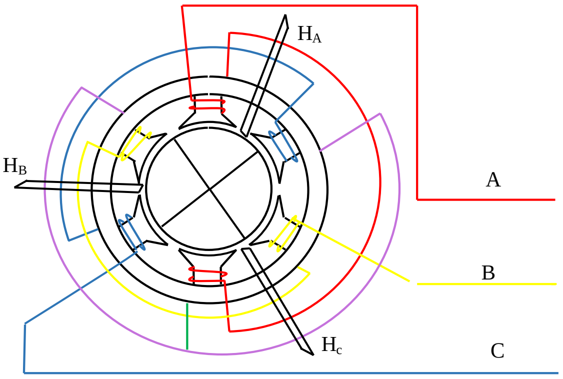


Figure 2.3: Cross-sectional of BLDC Motor with respect to Hall Effect Sensor.

2.4 Hall Effect Sensor in BLDC Motor

In most of the BLDC control applications, the Hall Effect Sensor is commonly used in order to determine the rotor position. These sensors are located in the motor housing and being offset from each other by 120º to make certain each sensor output is aligning with one of the electromagnetic circuit. The motor will rotates counter clockwise as there is a current pass through the motor windings. This flow of current will generates magnetic field in the stator which is North and South. Then, the rotor will rotates in order for the North pole in the rotor to align with the magnetic South generated in the stator. After that, the steps of rotation repeated with the same concept but different current flow [4]. The switching states to control the current flow through the motor and the relationship between the sensor output and the sector in which position of rotor is located are shown in Figure 2.4 (a) [5]. An inverter circuit connected to BLDC motor is shown in Figure 2.4(b). Each motor lead is connected to an upper and lower switching. The relation between the sector and the switching state are referred as the drive circuit firing which shown in Figure 2.4(a).

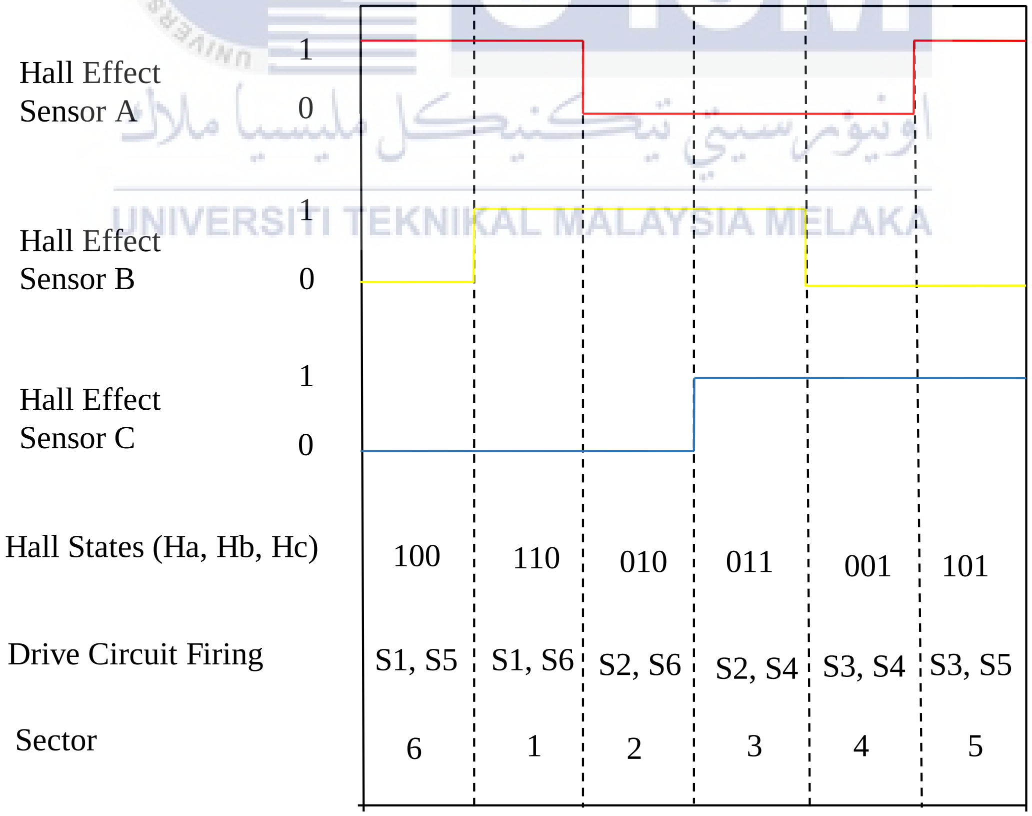


Figure 2.4(a): Output Graph of Hall Effect Sensor in BLDC Motor.

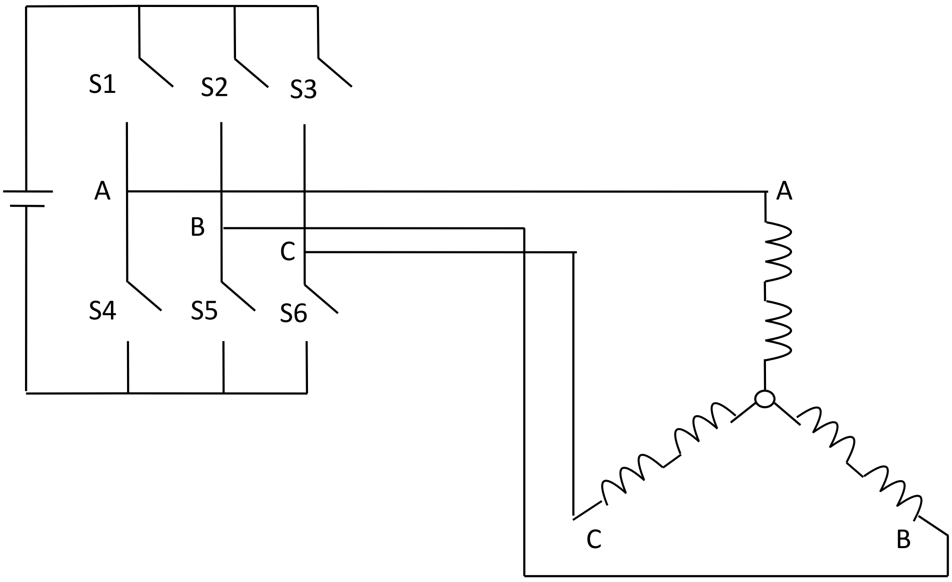


Figure 2.4(b): BLDC Motor Drive Circuit.

2.5 Related Previous Work

This section will be discussed about the schemes that is applicable for Brushless DC machine. The basic concepts and working operation for each method are being compared to get a better understanding on which controller is the most efficient to be used in controlling the BLDC motor.

2.5.1 Voltage Controlled of BLDC Motor

The concept for Voltage Controlled of BLDC motor strategy is the speed of BLDC motor is directly proportional to the voltage applied to the motor terminals [6]. As the voltage source is larger, the speed of the motor becomes faster. The main problem of this control strategy is it produces a very large current during start-up of the motor since it does not provide a current limitation due to no current sensor used. When a large demand is injected to the motor which caused the increasing of the speed, the torque produced is larger along with the larger current produced due to no current control. This is because their feedback is only based on the

Hall Effect Sensor. As for that, a linear power stage gives out high losses at high current and low voltage.

2.5.2 Direct Torque Control of BLDC Motor

The main drawbacks highlighted in the DTC method are high torque and flux ripples and the system switching frequency are not constant, varying with speed, load torque and the hysteresis band chosen [7]. Despite the disadvantages mentioned, researchers has been focusing to reduce the torque ripple and improving the switching frequency making it almost constant [8]. A simple dynamic over modulation method is employed in DTC with constant switching frequency. By modifying the flux error status produced the stator flux locus is controlled from circular to hexagonal shape. In the DTC of BLDC, the selection or situation of applying the zero voltage vectors is not the same as in the induction machines because the stator flux linkage will change even when the zero voltage vectors are selected since the magnets rotate with the rotor. Hence, zero voltage vectors are not considered in controlling the stator flux linkage in a BLDC system. Stator flux linkage should always be in motion with respect to the rotor flux linkage vector and the higher the stator vector rotation speed the faster the torque response is achieved.

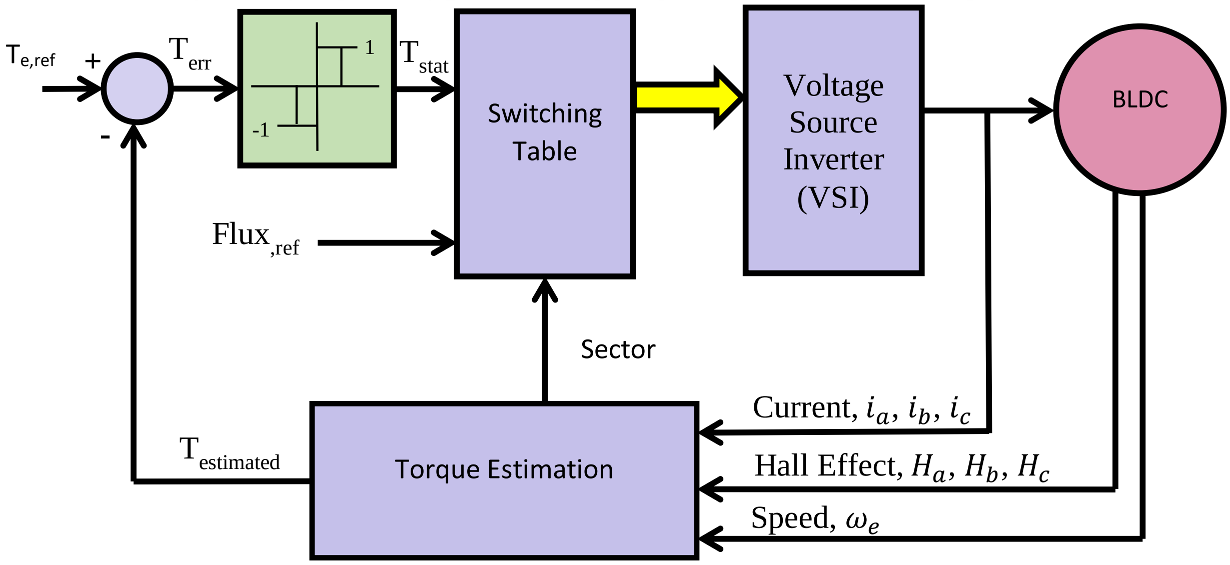


Figure 2.5.2: Structure of Direct Torque Controller (DTC) for BLDC motor

2.6 Proposed Torque Hysteresis Controller of BLDC Motor

Torque Hysteresis Control (THC) is a technique that can be used to replace the conventional motor which is Voltage Controlled. Due to the drawback of the Voltage Controlled that produces a very large current during start-up, the THC approaches is being introduced in order to control the current as well as controlling the torque. This problem can be overcome since THC has one current control loop for the structure which can limit the current. The hysteresis control scheme is one of the simplest close loop control as the value of controlled variable is forced to stay within certain limits around the reference value. The excellent torque dynamic performance can be achieved by using BLDC motor with the aid of Torque Hysteresis Controller. For this case, the 2-level hysteresis is being selected for controlling each phase current. It is eligible to generate a proper switching status that will be fed into the inverter by increasing or decreasing the phase current as long as the error is restricted within the hysteresis band.

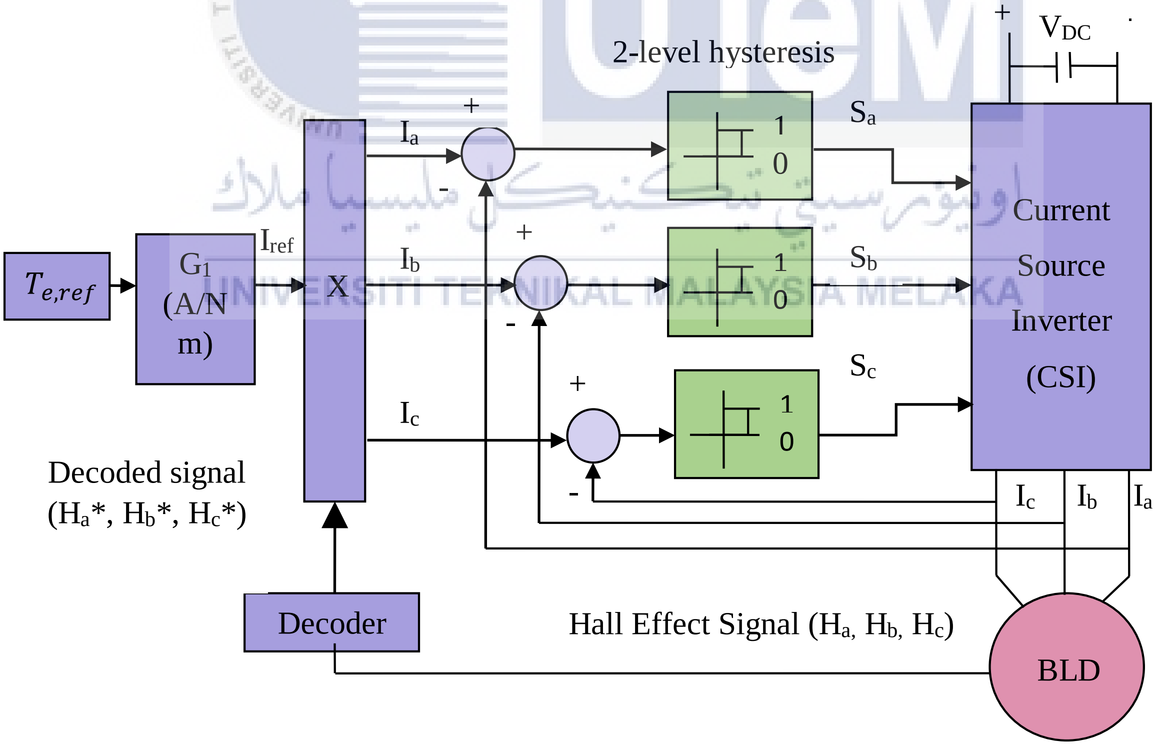


Figure 2.6: Structure of Torque Hysteresis Controller (THC) Drive for BLDC motor.

CHAPTER 3

METHODOLOGY

3.1 Significant Research of Principle Operation of Torque Hysteresis Controller

The appropriate controller to be used for the operation of BLDC machine is based on their purpose and objective. The reliability of the proposed strategy is important to ensure that the selected controller provide the optimum performance for the BLDC motor. Instead of using the conventional approaches which is Voltage Controlled of BLDC motor, the Torque Hysteresis Controller (THC) is the approaches that being selected in order to control the phase current and torque estimation of the Brushless Direct Current (BLDC) motor. Torque Hysteresis Controller (THC) approaches can overcome the constraint of using a Voltage Controlled of BLDC motor which has a drawback as well as producing a very high current overshoot since the THC method is able to provide a current protection. The controlled variable is forced to stay close to the reference by restricting the error in the bandwidth with define gap. For Torque Hysteresis Control (THC) strategy, it has one current control loop for the structure. As the current can be controlled, the torque can also be controlled. In order to establish torque control loop, it can be accomplished by using current hysteresis controller since current and torque is proportional to each other. THC established current control and thus, it generates current reference that will define the desired torque. The torque demand can be achieved with the presence of torque reference. In addition, the THC strategy shows its advantages in terms of the simplicity of the method and scheme for the system. Therefore, THC strategy displays more effective performance of BLDC motor rather than the Voltage Controlled with a lower cost.

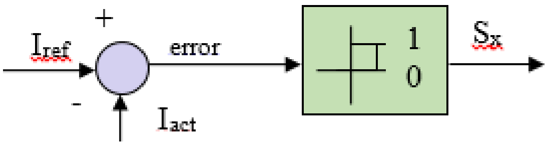


Figure 3.1: Block Diagram or Hysteresis Current Control.

3.2 Hysteresis Operation

The switching sequences of the inverter are compulsory to ensure the BLDC motor operates smoothly. As the hysteresis current control is the most important part in the THC scheme, it can determine its switching states within its predefined gap whether the switch is ON or OFF. The hysteresis current control implements the comparing signals between the reference current in its band gap. When the actual current touches the upper limit of the band, the displays output signal is 1 and whereas when the actual current touches the lower limit of the band, the displays output signal is 0. Figure 3.1.2 shows the output graph of hysteresis current control.

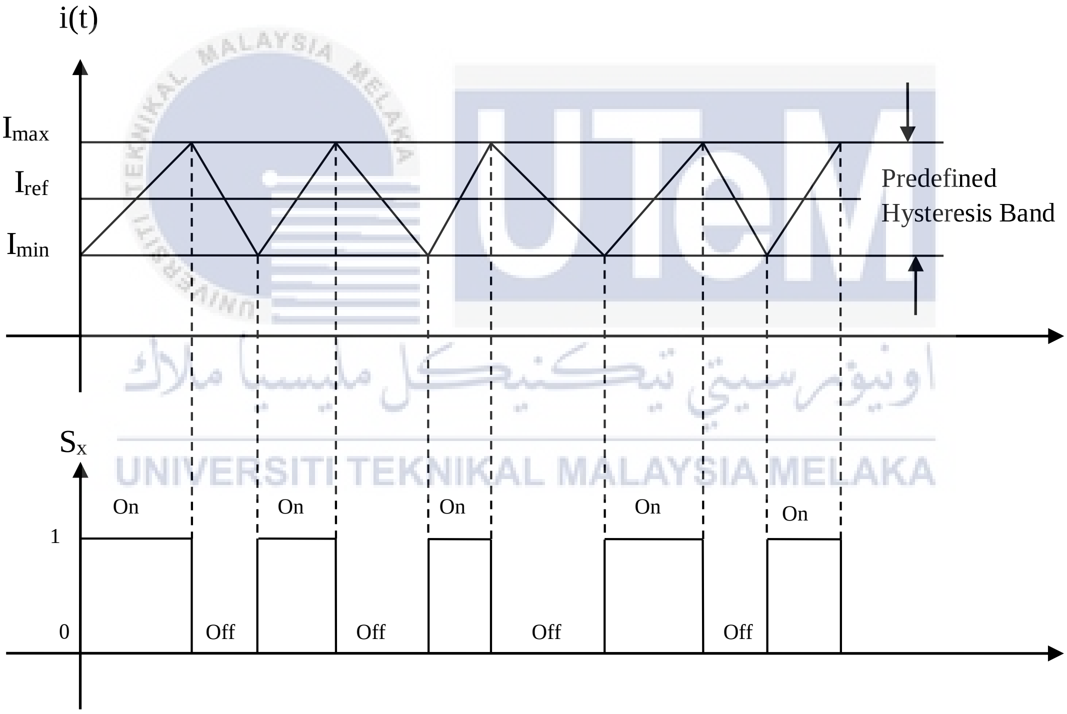


Figure 3.2: Output Graph of Hysteresis Current Switching Control.

3.3 Torque Estimation

Torque Hysteresis Controller has one current control loop for the structure. The lower switching is depends on the upper switching. The switching states are always complement to each other since each of the legs have the switching. As for that, the sum of the phase current must be zero and the reference current can be generated. The THC proposed strategy is compatible to be implemented to the BLDC motor as it is designed with the three-phase star connection with an ungrounded neutral point. Plus, the torque can be determined directly from the phase current.

$$\mathrm{I_{ref}} = \frac{\mathrm{T_{ref}}}{\mathrm{k_t}} \tag{3.1}$$

$$\mathrm{T_{e,total}} = \mathrm{T_{e,a}} + \mathrm{T_{e,b}} + \mathrm{T_{e,c}} = \mathrm{k_{t,a} i_a} + \mathrm{k_{t,b} i_b} + \mathrm{k_{t,c} i_c} \tag{3.2}$$

Where,

i_a, i_b, i_c = Phase currents

k_t = Torque constant for phase windings

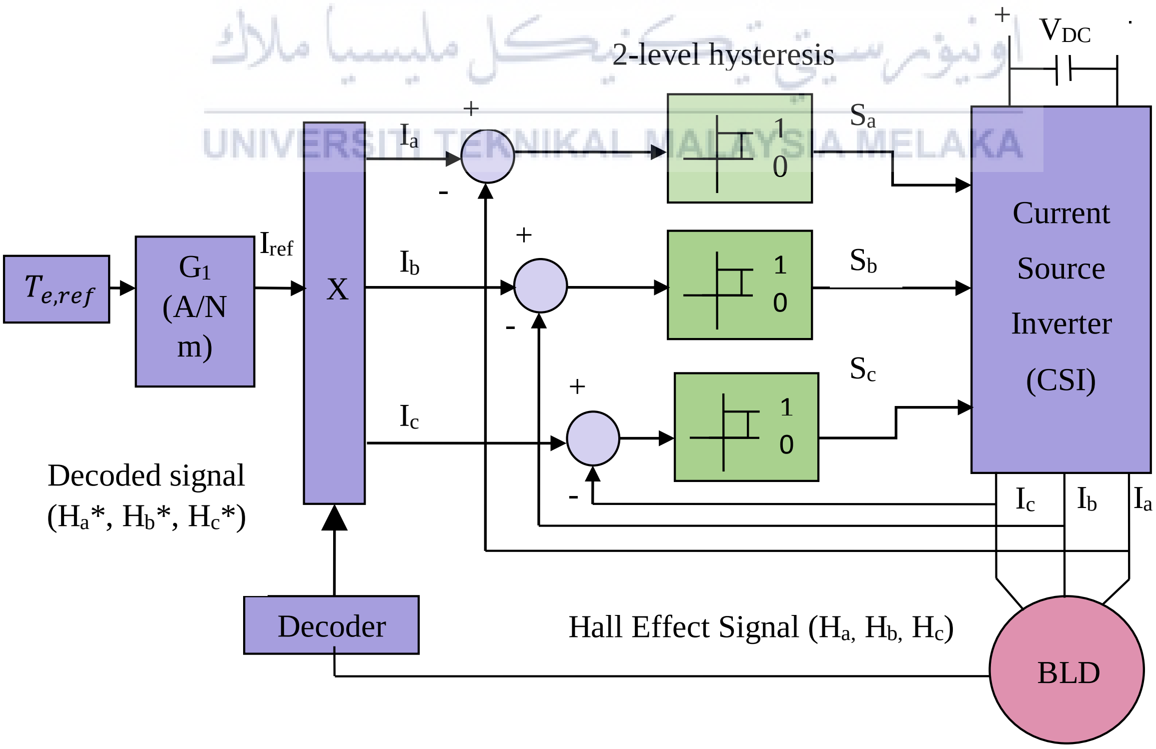


Figure 3.3(a): Structure of Torque Hysteresis Controller (THC) Drive for BLDC motor.

Figure 3.3 shows the basic blocks of BLDC motor which contains three phase stator circuit and mechanical part. The main difference compare to DC machine is the construction of the machine since it has three phase windings at the stator with n number of poles and the rotor equipped with permanent magnet which is positioned at the centre of the motor by the bearing. The rotor is not electrically connected to the stator and thus, it preventing arcing phenomena which causes the carbon to be produced as well as making an insulation failure. A few assumptions are made in order to reduce the mathematical complexity of the BLDC motor drive and they are symmetrical three-phase winding (1), no magnetic saturation (2), no hysteresis and eddy current losses (3), uniform air gap (4), mutual inductance is ignored (5) and armature reaction is ignored (6). The mathematical model of armature winding is expressed as:

$$V_a = i_a R + L\frac{di_a}{dt} + e_a \tag{3.31}$$

$$V_b = i_b R + L\frac{di_b}{dt} + e_b \tag{3.32}$$

$$V_c = i_c R + L\frac{di_c}{dt} + e_c \tag{3.33}$$

Where

V_a, V_b, V_c = Terminal voltages of phase a, b and c $[V]$

i_a, i_b, i_c = Stator current of phase a, b and c $[A]$

e_a, e_b, e_c = Back emf of phase a, b and c $[V]$

L = Per phase armature self-inductance $[H]$

R = Per phase armature resistance $[\Omega]$

The back emf are displaced by 120° from one phase to another and is expressed as:

$$e_a = K_e f(\theta_e)\omega_m \tag{3.34}$$

$$e_b = K_e f\left(\theta_e - \frac{2\pi}{3}\right)\omega_m \tag{3.35}$$

$$e_c = K_e f\left(\theta_e + \frac{2\pi}{3}\right)\omega_m \qquad (3.36)$$

Where

ω_m = Mechanical rotor speed $[rad.s^{-1}]$

K_e = Back emf constant $[V/rad \cdot s^{-1}]$

$f(\theta_e)$ = Trapezoidal function

θ_e = Electrical angle of rotor $[rad]$

Subtract equation (2) from (1) and (3) from (2) yield:

$$V_{ab} = R(i_a - i_b) + L\left(\frac{di_a}{dt} - \frac{di_b}{dt}\right) + (e_a - e_b) \qquad (3.37)$$

$$V_{bc} = R(i_b - i_c) + L\left(\frac{di_b}{dt} - \frac{di_c}{dt}\right) + (e_b - e_c) \qquad (3.38)$$

According to the Kirchoff's Current Law (KCL), the total phase current is equal to zero for wye-connected three-phase winding. Thus, the equation expressed is:

$$i_a + i_b + i_c = 0 \qquad (3.39)$$

$$i_c = -i_a - i_b$$

Substitute i_c from (3.39) to (3.38):

$$V_{bc} = R\big(i_b - (-i_a - i_b)\big) + L\left(\frac{di_b}{dt} - \frac{d_{(-i_a - i_b)}}{dt}\right) + (e_b - e_c)$$

$$V_{bc} = R(i_a + 2i_b) + L\left(\frac{di_a}{dt} + 2\frac{d_{ib}}{dt}\right) + (e_b - e_c) \qquad (3.40)$$

The electromagnetic torque produced by a BLDC motor can be expressed as:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \qquad (4.41)$$

Substitute equation (3.34), (3.35) and (3.36) into (4.11):

$$T_e = \frac{(K_t f(\theta_e)\omega_m)i_a + \left(K_t f\left(\theta_e - \frac{2\pi}{3}\right)\omega_m\right)i_b + \left(K_t f\left(\theta_e + \frac{2\pi}{3}\right)\omega_m\right)i_c}{\omega_m}$$

$$T_e = K_t\left[f(\theta_e)i_a + f\left(\theta_e - \frac{2\pi}{3}\right)i_b + f\left(\theta_e + \frac{2\pi}{3}\right)i_c\right] \qquad (4.42)$$

Where

T_e =Electromagnetic torque $[Nm]$

K_t =Torque constant $[Nm/A]$

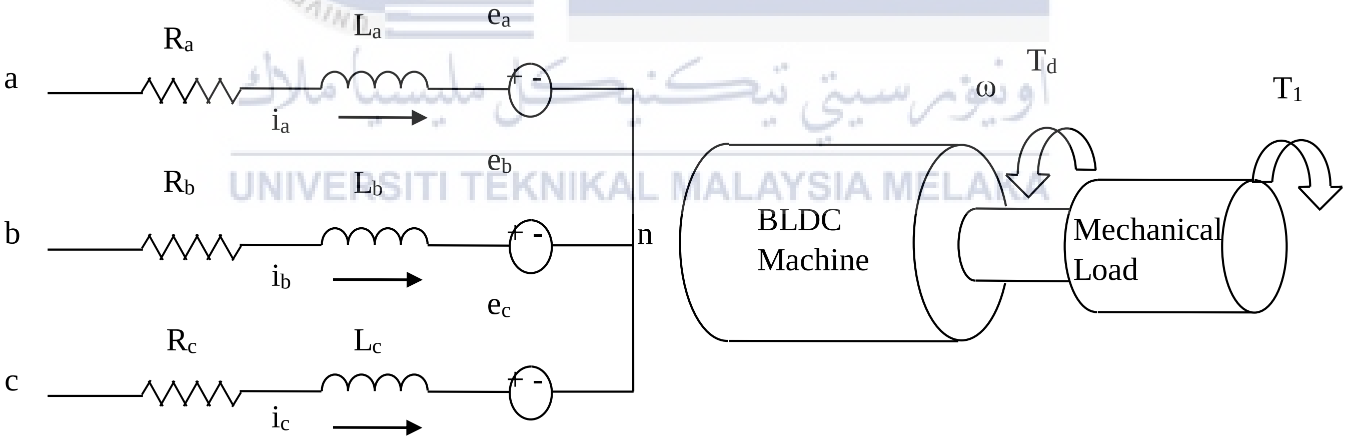


Figure 3.3(b): Three phase Brushless DC Machine Equivalent Circuit and Mechanical Model.

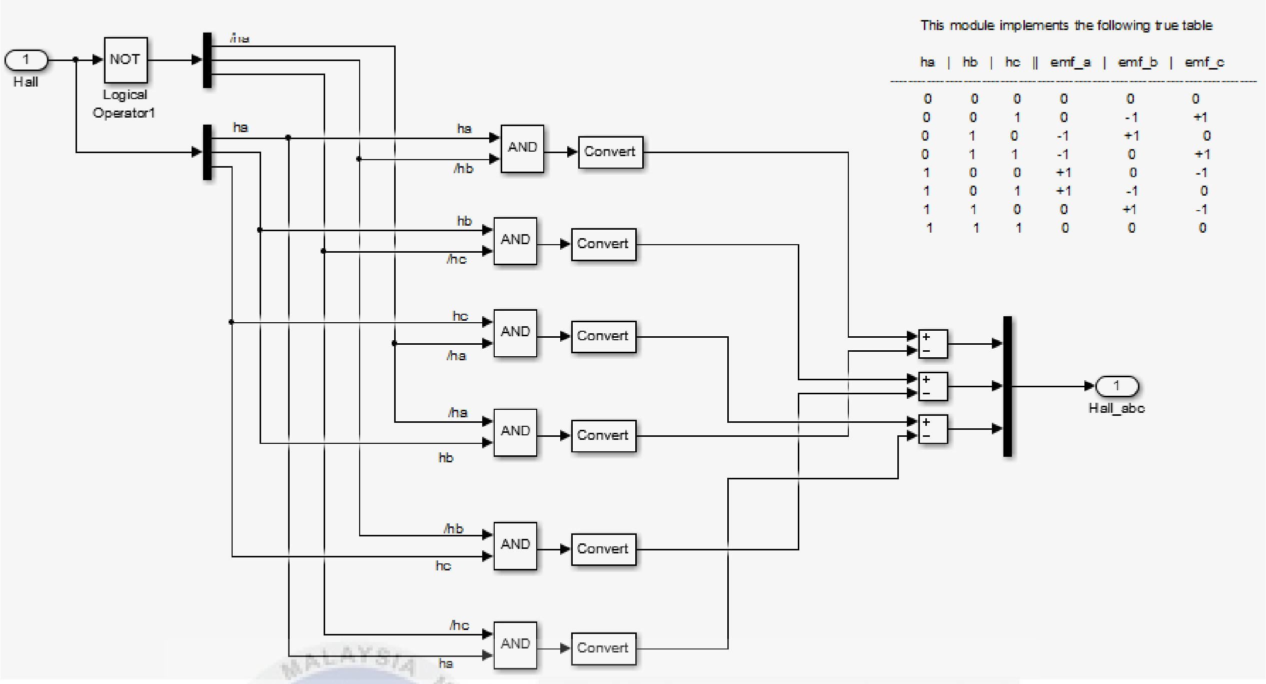
3.4 Simulation Model of Torque Hysteresis Controller (THC)

Each phase current that is controlled using a 2-level hysteresis comparator is responsible to produce appropriate switching status to be fed into the inverter. The results can be either to increase or decrease the phase current such that its error (or current ripple) is restricted within the hysteresis band. In such way, the reference current for each phase will have the same pattern waveform with the respective decoded signals.

Hall Effect Signal			Decoded Signal		
$\mathbf{H_a}$	$\mathbf{H_b}$	$\mathbf{H_c}$	$\mathbf{H'_a}$	$\mathbf{H'_b}$	$\mathbf{H'_c}$
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	-1	0
1	0	1	0	+1	-1
1	1	0	0	+1	-1
1	1	1	0	0	0

Table 3.4(a): Derivation of Decoded Signals based on Hall Effect Signals.

The simulation of decoder circuit in Figure 3.4(b) is constructed by referring to the Hall Effect Sensor and the Incremental Encoder table as shown in Table 3.4(c). The accurate triggering signal are compulsory to make certain the appropriate sequence of VSI is achieved and the system will run smoothly.



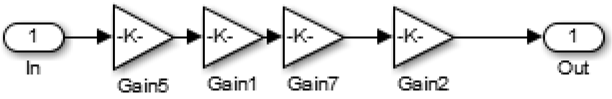
This module implements the following true table

```
ha  |  hb  |  hc  ||  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      +1         0         -1
1      0      1      +1        -1          0
1      1      0       0        +1         -1
1      1      1       0         0          0
```

Figure 3.4(b): Simulation of Decoder Circuit.

HA	HB	HC	EMFA	EMFB	EMFC
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

Table 3.4(c): Hall Effect Sensor and Incremental Encoder Table.



sampling time = 10e-3

Figure 3.4(d): Block Diagram of Estimated Speed.

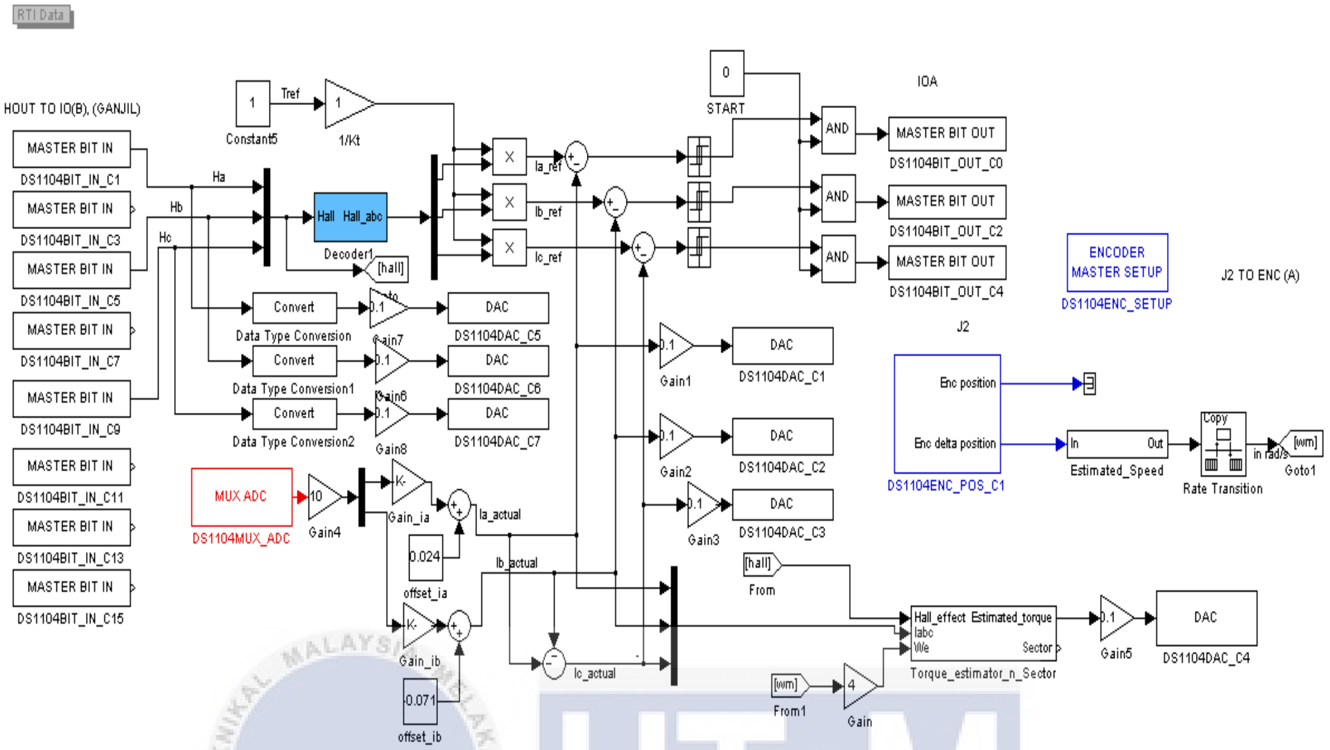


Figure 3.4(b): Complete Block Diagram of Simulation Control for BLDC Motor connecting with ControlDesk.

3.5 Experimental Set-up

The iDrive is designed along with other components such as power supply system, I/O terminal, FPGA, current measurement, BLDC Hall Sensor Terminals, Gate Driver Circuit and three-phase inverter. In order to control the driver with the motor, a dSPACE is used as an interconnection between the software and hardware. The iDRIVE controller kit is shown in Figure 3.5.

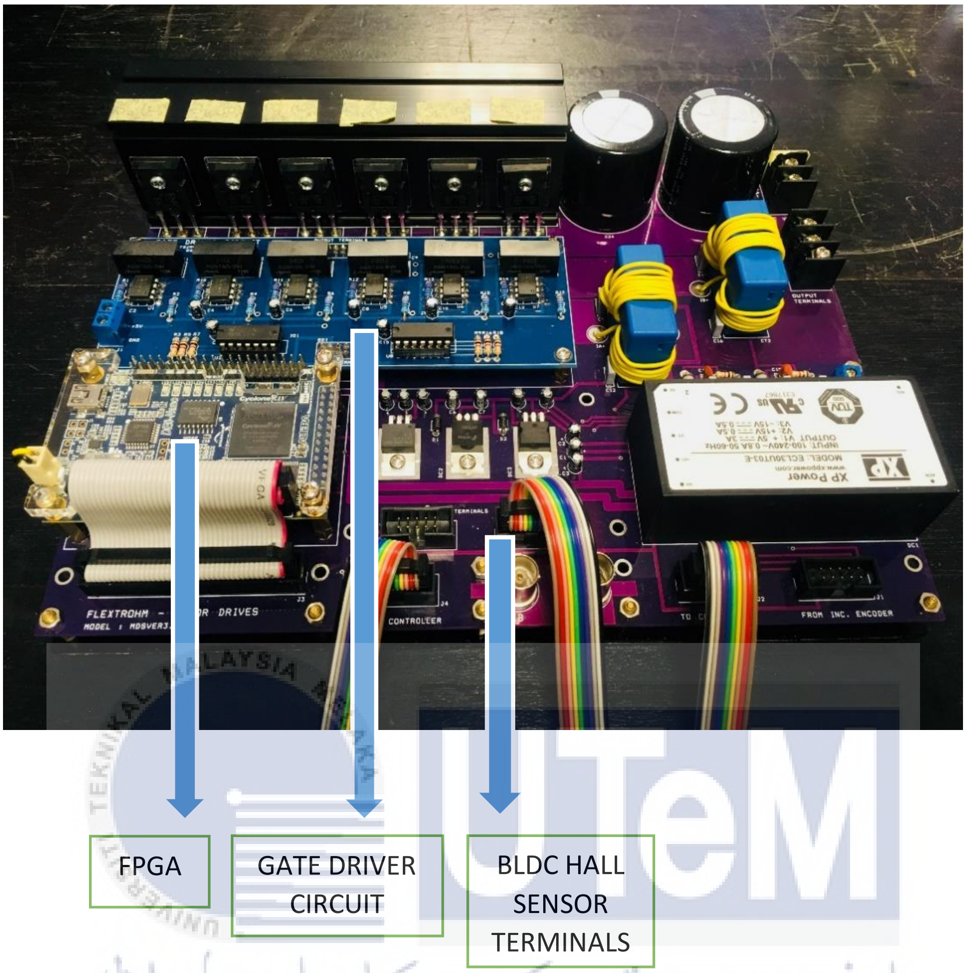


Figure 3.5(a): The iDRIVE Controller Kit.

Figure 3.5(b): BLDC Motor.

3.6 Flow Chart of Research Methodology

First and foremost, the research on the mathematical model of BLDC motor has been done in order to study on various control strategies that is more efficient for the operation of BLDC motor. The analysing processes are including the principle operation of THC and torque estimation. During this stage, the proposed control strategy must be clearly understood in terms of its theoretically, structure and control principle. Next, the simulation model development has been drawn since the simulation circuit is essential in implementing the motor drive system for THC of BLDC motor. The controlling scheme of THC is verified by the Simulink in MATLAB. In this stage, the parameters of the control scheme have been tested. The simulation circuit is being troubleshoot until obtained the desired output. If the improvement of the simulation is verified, it can proceed to the next step which is hardware implementation. A research on the potential hardware that will be used for the experimental procedure should be done after being able to verify the effectiveness of the completing simulation. If the improvement of the hardware implementation is verified, the last step should be done is performing the report writing. The report must cover up the literature review, research methodology, simulation and experimental process, results and discussion and last but not least, the conclusion and future works that being considered. The citation, reference and appendix are included for easy reference.

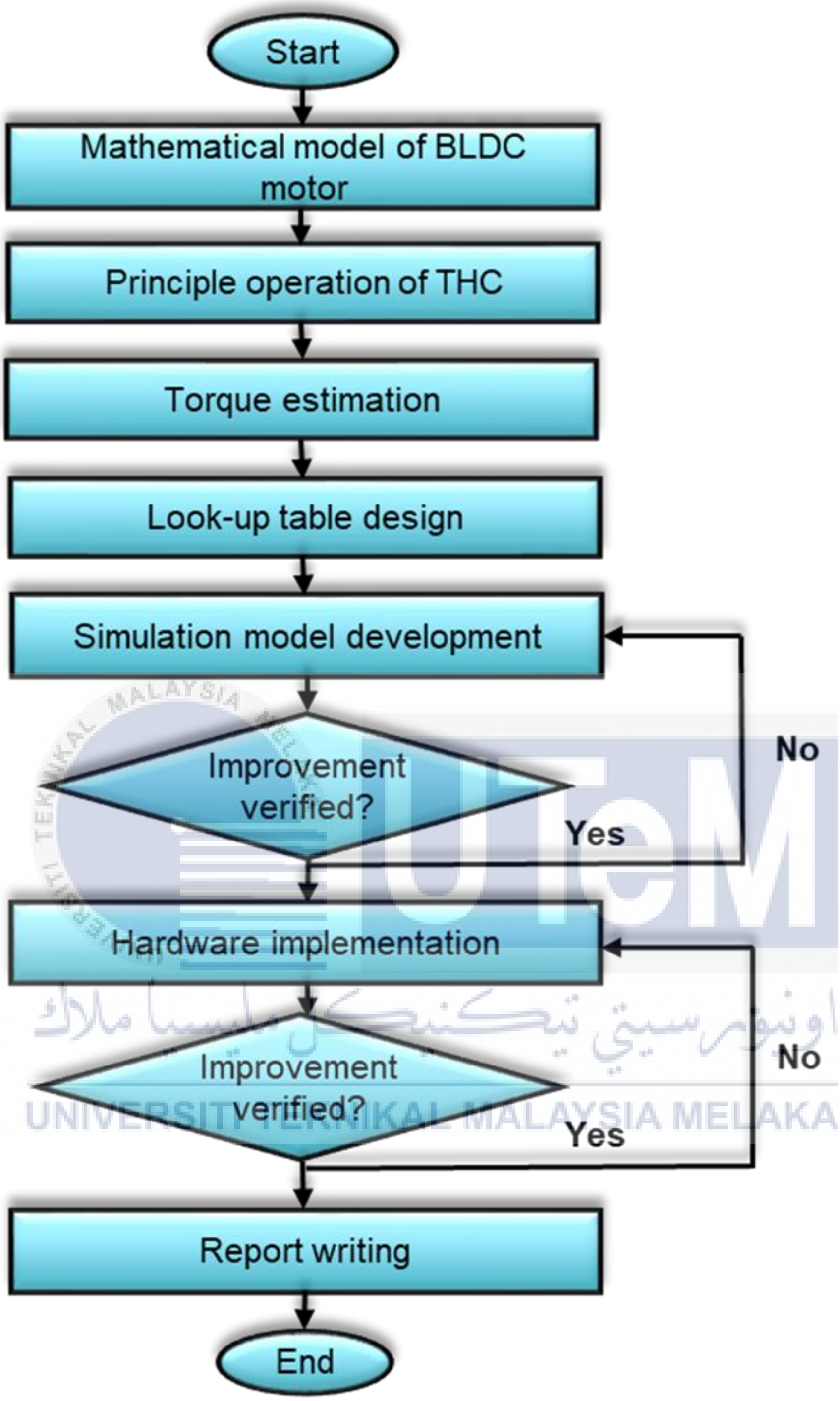


Figure 3.6: Flowchart of the Research Project.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This project is expected to achieve the desired objective which is the implementation of Torque Hysteresis Controller (THC) for BLDC motor utilizing DSpace 1104. The simulation were performed by using the Simulink in MATLAB software. The results obtained from the simulation of THC for BLDC motor is analyse in terms of the current and torque produced and compared with the preliminary results, which is the Voltage Controlled of BLDC motor. The theory from the previous chapter will be proved in this chapter by simulation and explanation regarding the simulation result obtained for the proposed strategy.

4.2 Preliminary Result of Voltage Controlled for BLDC Motor

Figure 4.2 shows the simulation for preliminary result of current produced by Voltage Controlled for BLDC Motor. The purple and blue colour represents the logical operator while the red colour represents the acceleration current measurement. The starting voltage for DC link is set up to 100 V. When the voltage is suddenly increases to 500 V during simulation running, the output current is increases rapidly since it cannot be controlled. If the injected voltage is high, the speed of the motor will increases. Thus, the torque becomes larger as the current becomes larger due to no current loop as there is no current sensor used in the experiment. As for that, the losses becomes higher and its efficiency is decreases. The shape of the waveform shown is depends on the motor parameter.

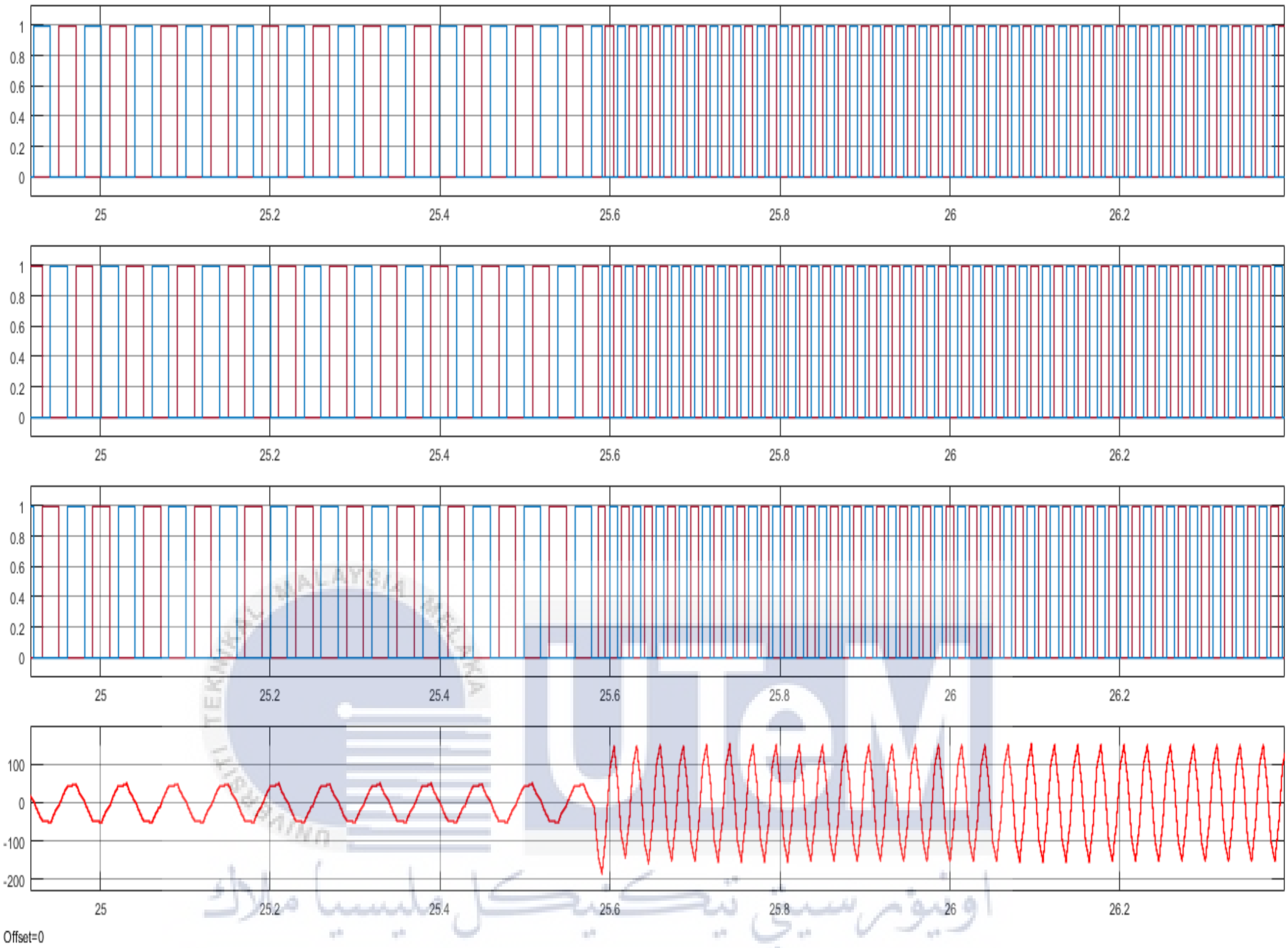


Figure 4.2: Simulation for Preliminary Result of Current Produced by Voltage Controlled for BLDC Motor.

4.3 Parameters Setting for Simulation of Proposed THC Technique for BLDC Motor

Figure 4.3 displays the parameters value for THC of BLDC Motor. The experimental setup consists of hysteresis current control, accurate speed and position information, a secure three phase DC/AC inverter, digital signal processor and an appropriately size BLDC machine and load.

TYPES OF PARAMETERS	**PARAMETERS**	**VALUE**
Control System	Hysteresis band	0.1 A
	Sampling time	50 μs
BLDC Motor	Stator phase resistance Rs (Ω)	0.2 Ω
	Stator phase inductance Ls (H)	8.5 mH
	Flux linkage established by magnets	0.175 V.s
	Torque constant	1.4 Nm/A
	Moment of inertia	3
	Friction factor	20e-6
	Pole pairs	4

Table 4.3: Parameters Value for THC of BLDC Motor.

4.4 Evaluation of Proposed THC Technique for BLDC Motor

The relation between Hall Effect Signals Ha, Hb and Hc with decoded signals for phase a, b and c are shown in Figure 4.4(a), 4.4(b) and 4.4(c) respectively. The dark blue, light blue and magenta colour represents the Hall Signals Ha, Hb and Hc respectively while the green colour represents the decoded signal for phase a (Ha’), phase b (Hb’) or phase c (Hc’). Each phase have different angle of rotation for the motor and thus, the experimental results obtained is based on the changes in position of Hall Effect Signals Ha, Hb and Hc with each phase.

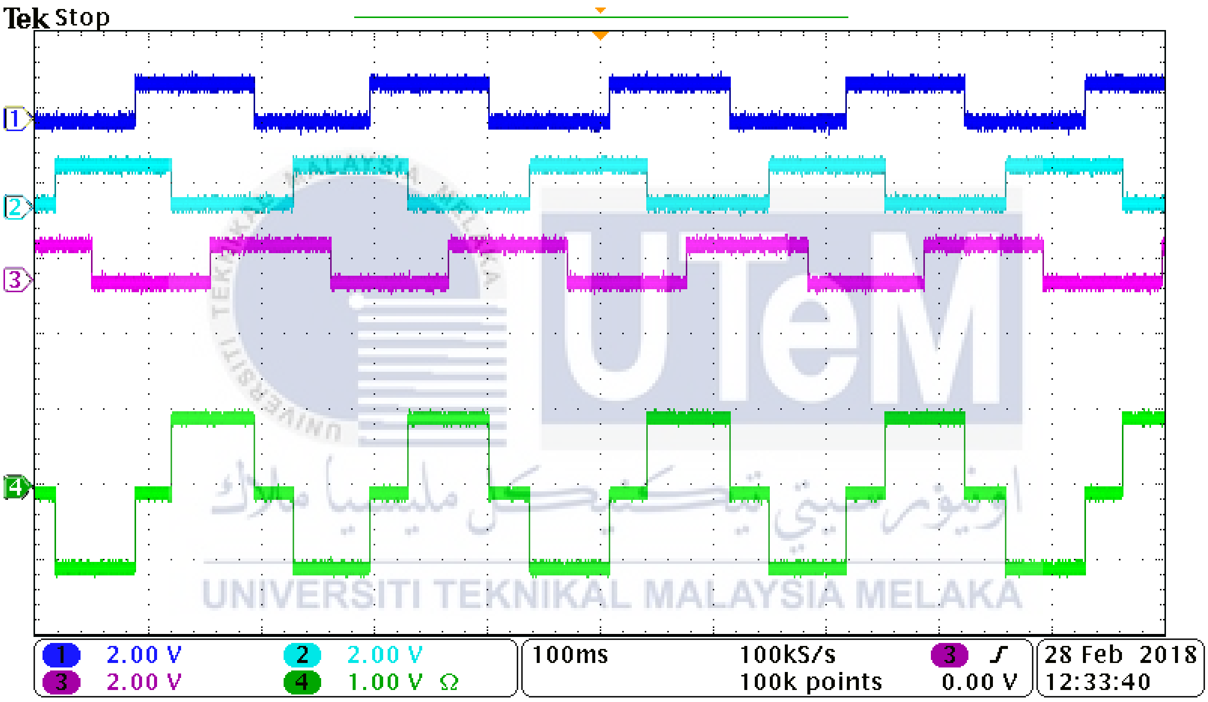


Figure 4.4(a): Experimental Result of Ha’ for 30 V.

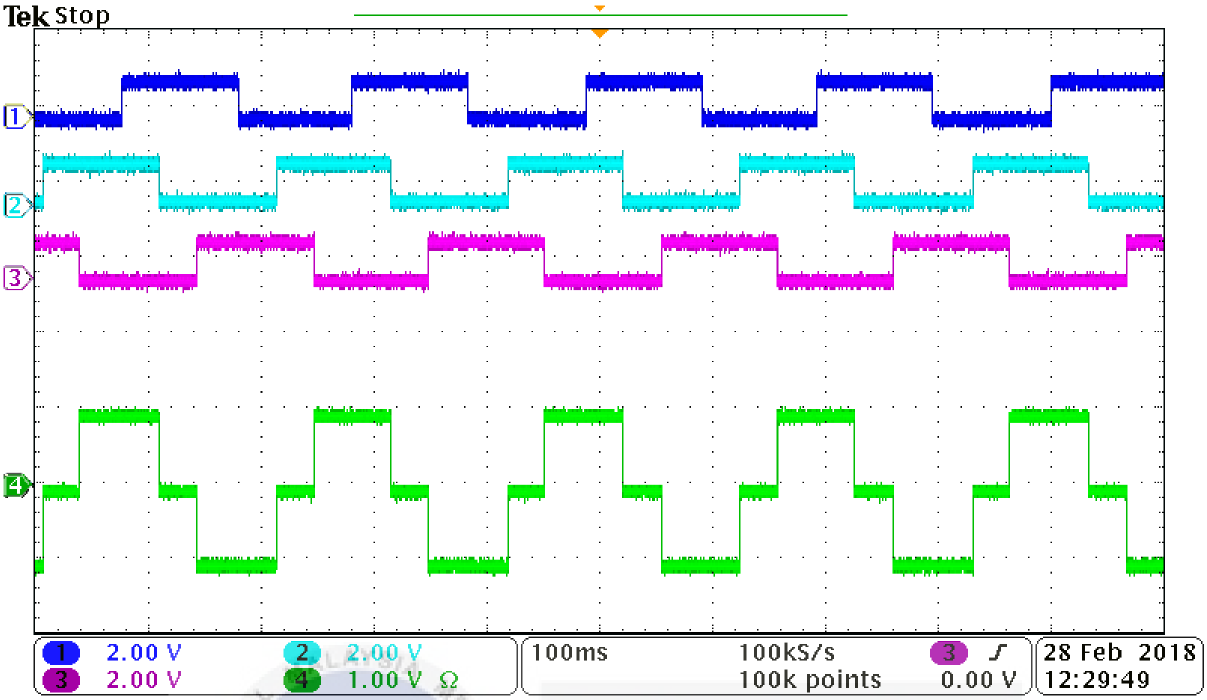


Figure 4.4(b): Experimental Result of Hb’ for 30 V.

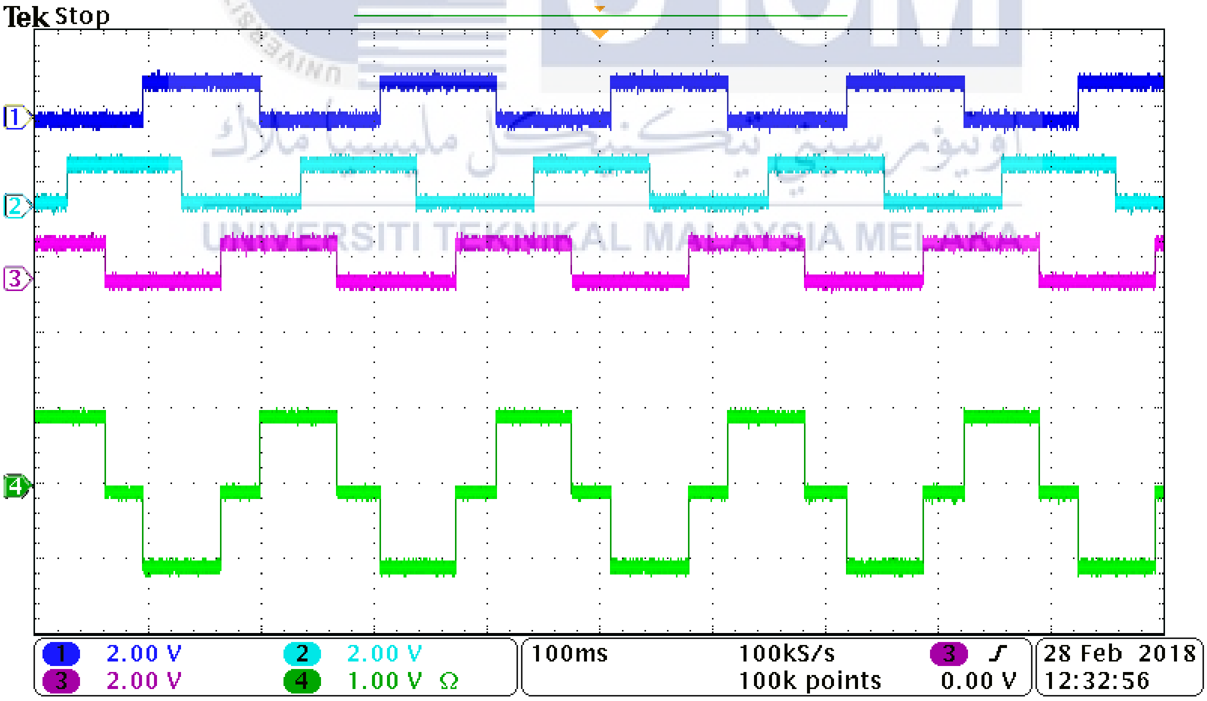


Figure 4.4(c): Experimental Result of Hc’ for 30 V.

The relation between Hall Effect Signals Ha, Hb and Hc with the reference current for phase a, b and c are shown in Figure 4.4(d), 4.4(e) and 4.4(f) respectively. The dark blue, light blue and magenta colour represents the Hall Signals Ha, Hb and Hc respectively while the green colour represents the current reference for phase a (Ia), phase b (Ib) or phase c (Ic). The generation of reference current for each signals is based on the multiplication of reference current with each decoded signal.

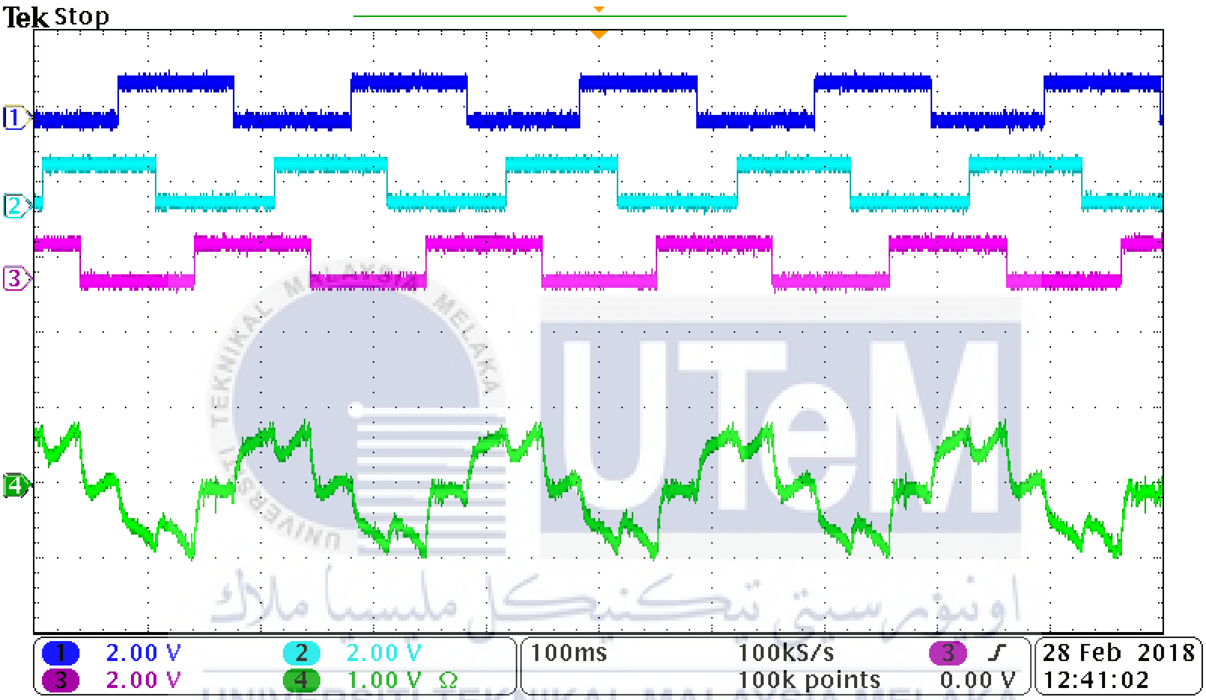


Figure 4.4(d): Experimental Result of Ia reference for 30 V.

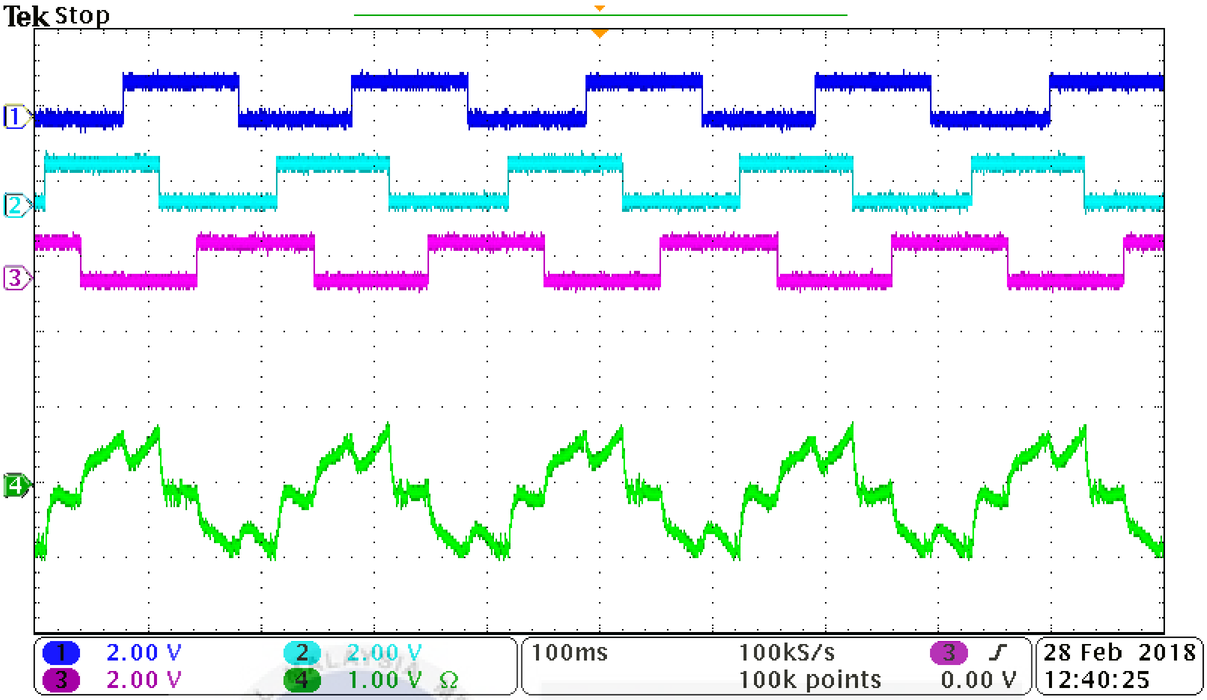


Figure 4.4(e): Experimental Result of Ib reference for 30 V.

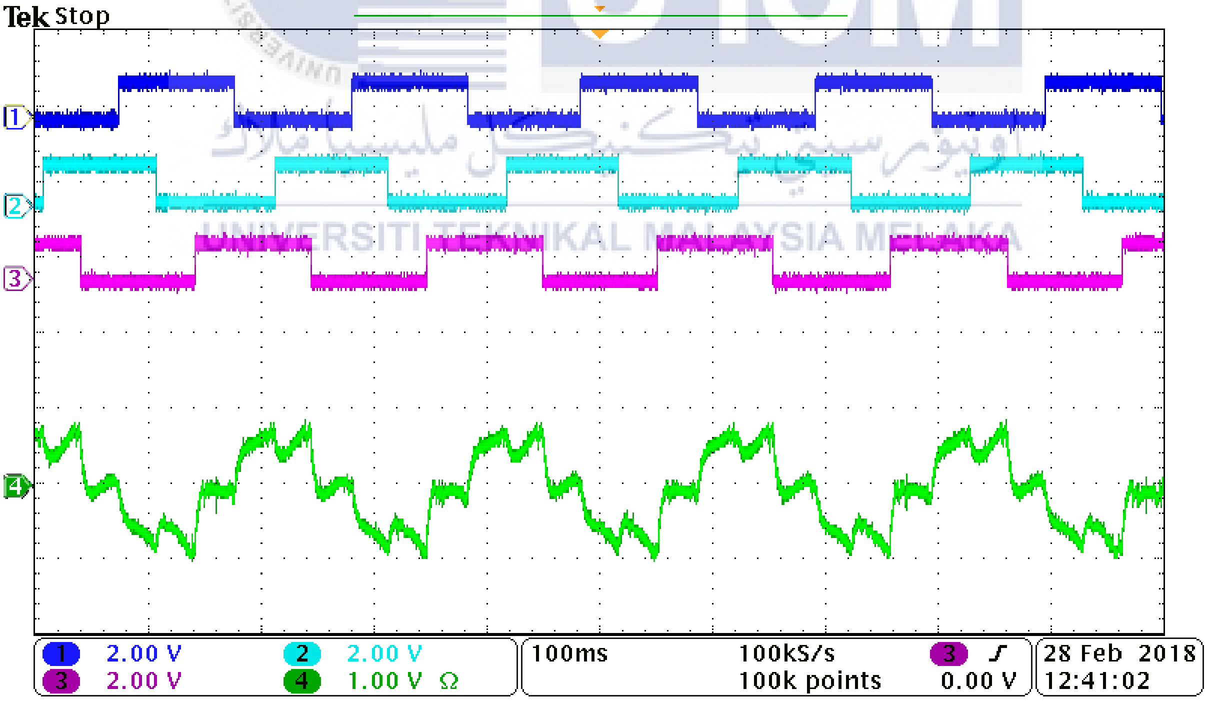


Figure 4.4(f): Experimental Result of Ic reference for 30 V.

The shape of the profile current is depends on the Hall Signals and the magnitude value is depends on the multiplication with the reference current. The value of the torque demand can be adjusted by using the slider gain (potentiometer). The gain have two modes which is adjustable gain (slider gain) and step change (push button). For instance, the step change from lower to higher bandwidth as in Figure 4.4(g). When a step change is injected from 0.5 Nm to 1.5 Nm, the current peak increases because the magnitude current is rely on the reference torque while the amplitude of current profile is depends on the torque demand. The results obtained for Figure 4.4(h) is in vice versa when the step change given is from 1.5 Nm to 0.5 Nm, which is from higher to lower bandwidth.

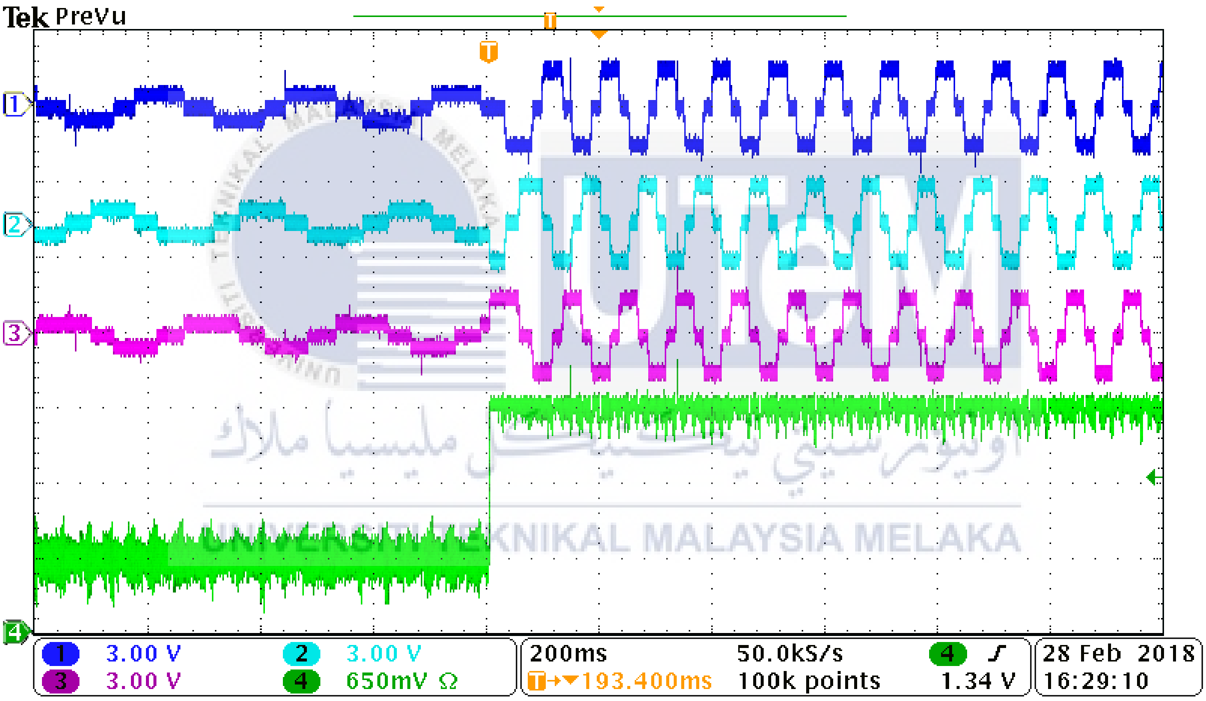


Figure 4.4(g): Experimental Result of lower to higher bandwidth for 100 V.

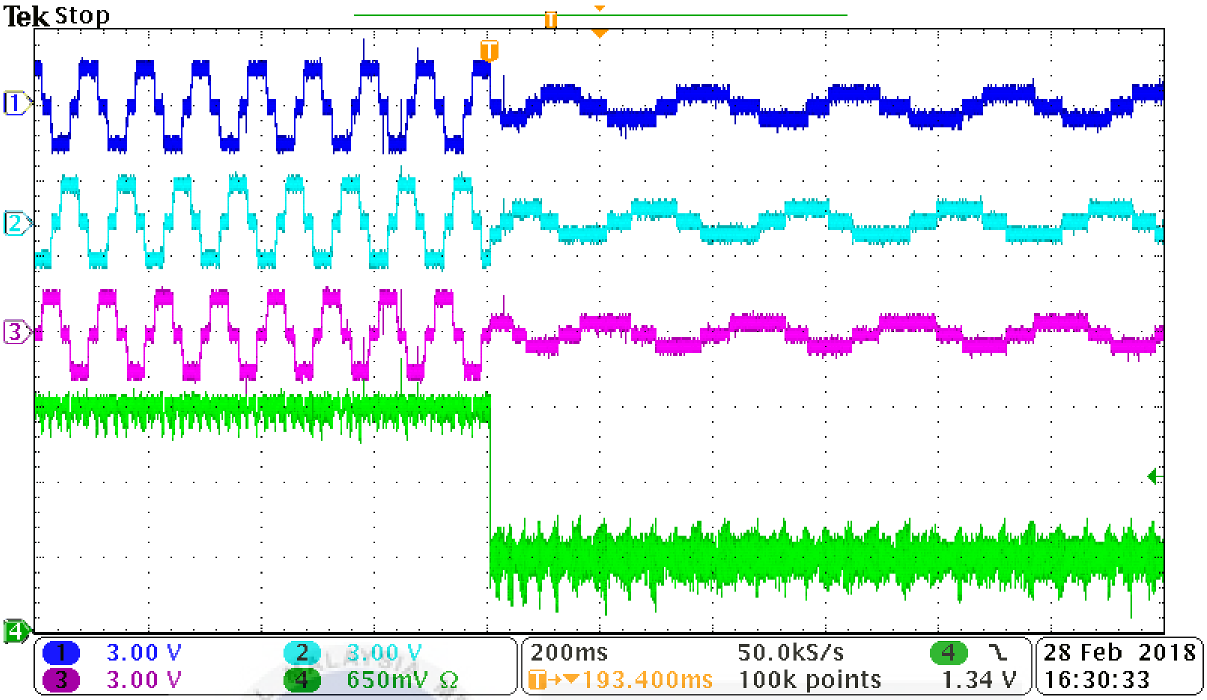


Figure 4.4(h): Experimental Result of higher to lower bandwidth for 100 V.

Figure 4.4(i), 4.4(j) and 4.4(k) shows the experimental result of higher, medium and lower bandwidth respectively. When the torque demand is low, the current magnitude .is low. When the torque demand is high, the current is still regulate following the reference which can counter the case for overshoot current in Voltage Controlled. The value of the current can be limited due to the presence of current control loop. If the gap between the upper and lower bandwidth is large, the current ripple becomes large and the frequency becomes high. This is because when the gap between two bandwidth is large, the time taken for the error to travel from lower bandwidth to higher bandwidth is longer. As a results, it produces high frequency due to the rapid movement of error.

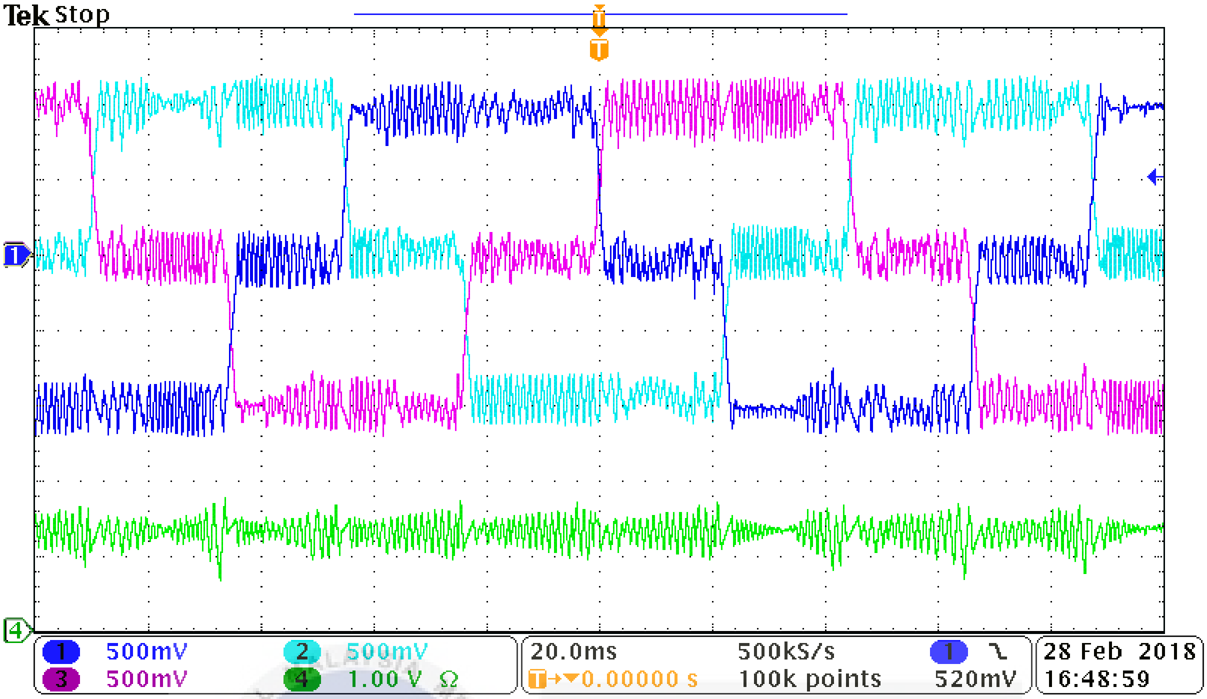


Figure 4.4(i): Experimental Result of higher bandwidth for 100 V.

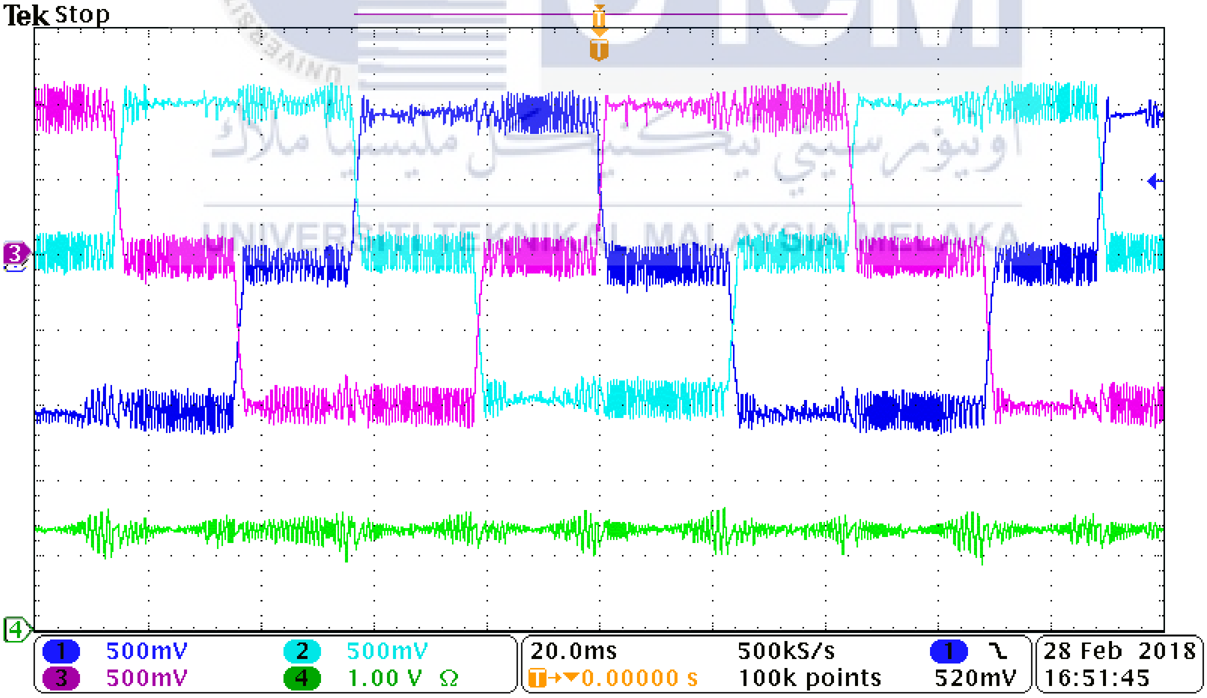


Figure 4.4(j): Experimental Result of medium bandwidth for 100 V.

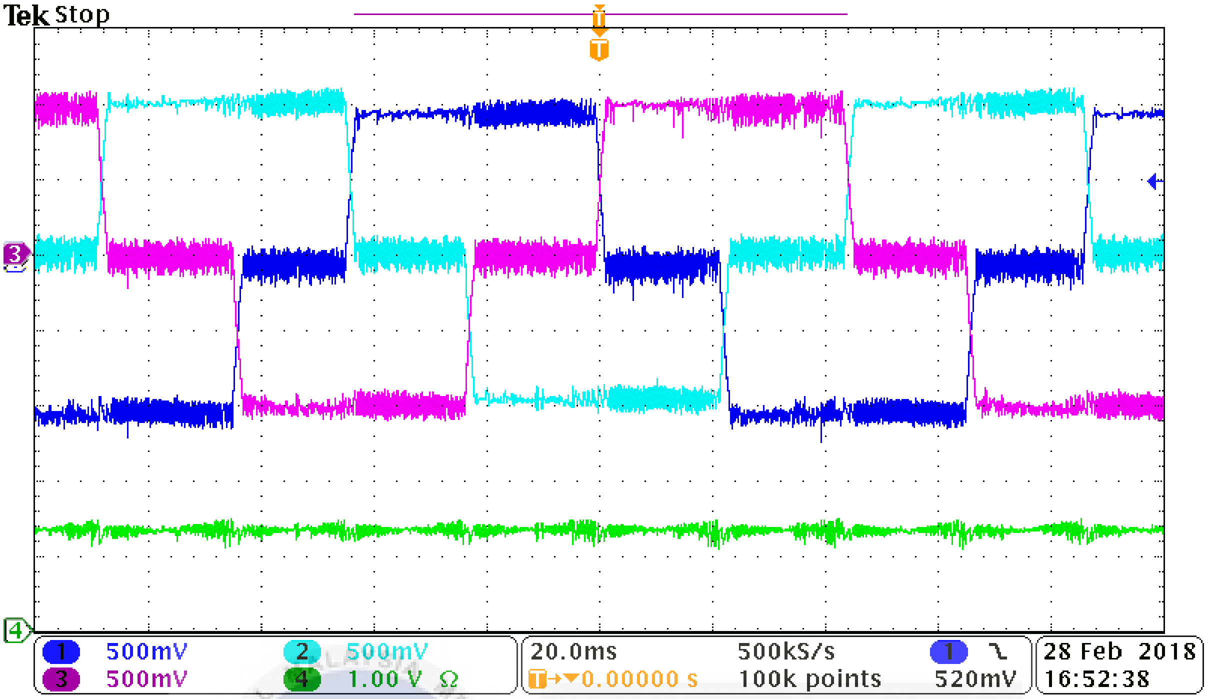


Figure 4.4(k): Experimental Result of lower bandwidth for 100 V.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.0 CONCLUSION

As for conclusion, this report is mainly contributes in implementing the Torque Hysteresis Controller technique using BLDC motor. The possibility for improvement is still wide which can include many areas to be taken in a research study. Although THC of BLDC motor has been around for quite sometimes, researcher still focus on this method in the motor drive research area. The desired objective are successfully achieved based on the simulation results obtained by Simulink in MATLAB software for proposed technique which is THC of BLDC motor. Based on the research and simulation result on THC of BLDC motor, it is proven that the Torque Hysteresis Controller is a better controller to be used in order to obtain a better motor performance and controlling the current measurement compared to other controller like Voltage Controlled.

5.1 Future Work

The main problem of THC technique is it produces a variable switching and as a results, the frequency is uncertain. The recommendation that can be conducted for the future work is proposing the carrier technique in order to produce a constant switching. This approaches can maintain the fourier and the side bandwidth produced is significant. By using this method, the ripple can be reduced with the injection of triangular waveform. The output from the torque reference and status flux is compared with the carrier to ensure the carrier waveform is limited within the bandwidth.

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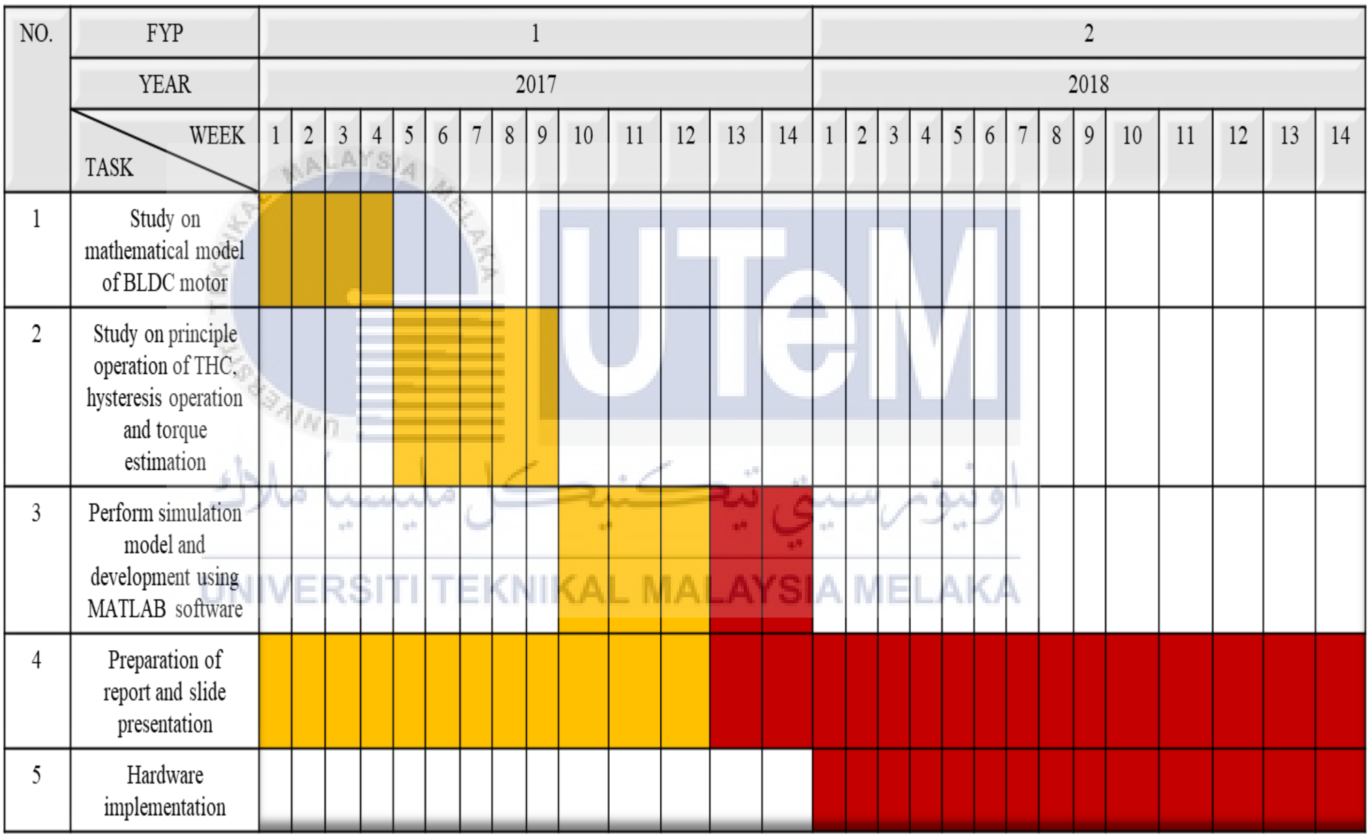
APPENDICES

APPENDIX A

GANTT CHART



NO.	FYP	1														2													
	YEAR	2017														2018													
	WEEK TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Study on mathematical model of BLDC motor	🟨	🟨	🟨	🟨																								
2	Study on principle operation of THC, hysteresis operation and torque estimation					🟨	🟨	🟨	🟨	🟨																			
3	Perform simulation model and development using MATLAB software										🟨	🟨	🟨	🟥	🟥														
4	Preparation of report and slide presentation	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
5	Hardware implementation															🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

APPENDIX B

MATLAB SIMULATION