MODELING AND SIMULATION OF DIRECT TORQUE CONTROL OF BRUSHLESS DC MOTOR DRIVES

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

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(2014)

DECLARATION

I declared that this report entitle "Modeling and Simulation of Direct Torque Control of Brushless DC Motor Drives" 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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Supervisor's Signature : ……………………………………..

Supervisor's Name : ……………………………………..

Date : ……………………………………..

DEDICATION

Specially dedicated to my family

ACKNOWLEDGEMENT

In the name of ALLAH, Most Generous and Most Merciful. With the deepest sense of gratitude to ALLAH the Almighty for giving me strength and ability to complete this final year project report. These special thanks goes to my supervisor namely Dr Auzani Bin Jidin for his cooperation and advice that really help me to understand about my topic.

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ABSTRACT

Direct Torque Control (DTC) operates in two-phase conduction mode; where only two-phase produce switching at one time while the switching in conventional Torque Hysteresis Controller (THC) method resulted in three-phase. Thus, the significant of study is to prove that the switching frequency in THC is lower than DTC for every speed operating ranges. The problem in THC method is poor torque regulation performance due to the current or torque ripple is not restricted within predefined hysteresis bandwidth. As for DTC, the problem occur when small hysteresis bandwidth produce high switching frequency than THC in order to minimize torque ripple. This research project aims to model and simulate the DTC of BLDC and make comparison between the switching frequency and torque/current control performances produced in DTC and THC of BLDC drive. This simulation is conducted by using Matlab/ Simulink. The first things to look at are the mathematical modeling of BLDC motor. The anatomy of motor is required to understand basic operation of BLDC motor drive. Besides, principle of DTC and theory about THC are also important in order to analyze the performance of DTC and THC. The outcomes resulted from the simulation shows that DTC have better torque regulation due to optimum voltage vector selection but higher switching frequency than THC. As for the conventional THC, it produces poor torque regulation performance and low switching frequency than DTC. It is proved that both THC and DTC have its own advantages and disadvantages.

ABSTRAK

Kawalan Terus Daya Kilas (DTC) beroperasi dalam mod pengaliran dua- fasa; di mana hanya dua- fasa menghasilkan arus pada satu masa manakala pensuisan dalam konvensional Tork Histeresis Controller (THC) menghasilkan tiga fasa. Oleh itu, kepentingan kajian adalah untuk membuktikan bahawa kekerapan pensuisan dalam THC adalah lebih rendah daripada DTC bagi setiap kelajuan julat operasi. Masalah dalam kaedah THC adalah semakin prestasi peraturan tork kerana riak semasa atau tork tidak terhad dalam ditentukan histerisis bandwidth. Bagi DTC, masalah berlaku apabila jalur lebar histerisis kecil menghasilkan frekuensi pensuisan tinggi daripada THC untuk mengurangkan tork riak. Projek penyelidikan ini bertujuan untuk menjadi dan mensimulasikan DTC daripada BLDC dan membuat perbandingan antara kekerapan switching dan persembahan kawalan tork / semasa dihasilkan di DTC dan THC pemacu BLDC. Simulasi ini dijalankan dengan menggunakan Matlab / Simulink . Perkara pertama yang perlu dilihatt adalah model matematik BLDC motor. Anatomi motor diperlukan untuk memahami operasi asas BLDC memandu motor. Selain itu, prinsip DTC dan teori mengenai THC juga penting untuk menganalisis prestasi DTC dan THC. Hasil daripada simulasi menunjukkan bahawa DTC mempunyai peraturan tork yang lebih baik tetapi kekerapan suis lebih tinggi daripada THC. Bagi THC konvensional, ia menghasilkan prestasi yang lemah peraturan tork dan frekuensi pensuisan rendah daripada DTC. Ia membuktikan bahawa kedua-dua THC dan DTC mempunyai kelebihan dan kekurangan tersendiri.

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BLDC	–	Brushless DC Motor
CSI	–	Current Source Inverter
DTC	–	Direct Torque Control
FOC	–	Field Oriented Control
IM	–	Induction Motor
PMSM	–	Permanent Magnet Synchronous Motor
THC	–	Torque Hysteresis Control
VSI	–	Voltage Source Inverter

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CHAPTER 1

INTRODUCTION

1.1 Overview

In recent years, the research on brushless DC motor (BLDC) drives has received enormous attention due to its excellent dynamic response, high efficiency, wide speed and high torque capability performances. There are many methods to control the torque, flux and current in BLDC motor. These includes the use of Torque Hysteresis Controller (THC), Field Oriented Control (FOC) and Direct Torque Control method. Figure 1.1 shows the BLDC motor control.

THC is one of the technique to control the torque and phase current of the BLDC machine. This method is used to replace the conventional voltage control that results in very high current overshoot. The value of torque and current stay within certain limit in hysteresis band by using THC, as it will provide current protection. However, the drawback of THC is poor current or torque regulation performance. This disadvantage of THC encourages the development of two-phase DTC in order to have better regulation performance [1]. However, the use of DTC may give another problem namely higher switching frequency eventhough it operates based on two-phase conduction mode. Later, this thesis will prove that high switching frequency in DTC compared to that obtained in THC.

As for the FOC, it is use to decouple the control of flux and torque. The main disadvantages of FOC is because it is complex than DTC due to the presence of co-ordinate transformation that requires information on the instantenous positon of the appropriate flux space vector [2].

Theory and principles of Direct Torque Control was introduced in the mid 1980's [2]. It is a newer concept and have been quickly accepted in industry in only ten years rather than twenty years for vector control [2-3]. First implementation of DTC was originally developed for induction machine drives. However, this project are focusing on DTC of BLDC. These two fundamental of DTC of IM and DTC of BLDC are having slightly different and will be explained further. DTC requires simple signal processing method. In its basic form, DTC give simple control structure as it is sensitive to only variation of stator resistance [3,21]. Figure 1.2 and Figure 1.3 shows the control stucture between DTC and FOC. DTC recognizes that, it is possible to control flux and torque directly. The idea of DTC development was initiated from conventional vector control strategy. In vector control approach, the flux and torque able to be controlled instantenously using the respective producing current components. Similarly to that of DTC approach where the flux and torque can be controlled simultaneously based on the respective flux and torque error status to select the suitable voltage vectors for satisfying the demands.

Error exist in torque and flux can be used directly to drive the inverter without any current control loops that necessary for co-ordinate transformation in conventional FOC [3] is the basic idea of DTC. In order for the errors in flux and torque remain within the hysteresis bands, the output from the flux and torque controller are used to determine which of the possible inverter states should be applied to the machine terminal. In torque mode operation, correct estimation of stator flux and torque is very important for accurate operation of hysteresis controller. Thus, MATLAB/SIMULINK will be used as a simulation tools to analyze the performance of THC and DTC.

In addition, an accurate mathematical model of a Brushless DC Motor (BLDC) is important in DTC. It is fact that BLDC have become current trend for many applications. Computer hard drives, electronic-component cooling fans, electric or hybrid car are those that rely on BLDC motor [4-6]. BLDC known as synchronous motor because the rotor and stator turn at the same frequency. Thus, it eliminating slip that is normally seen in induction machine. Besides, BLDC is capable of providing large amount of torque over a vast speed range and is consider to be high performance motor drives.

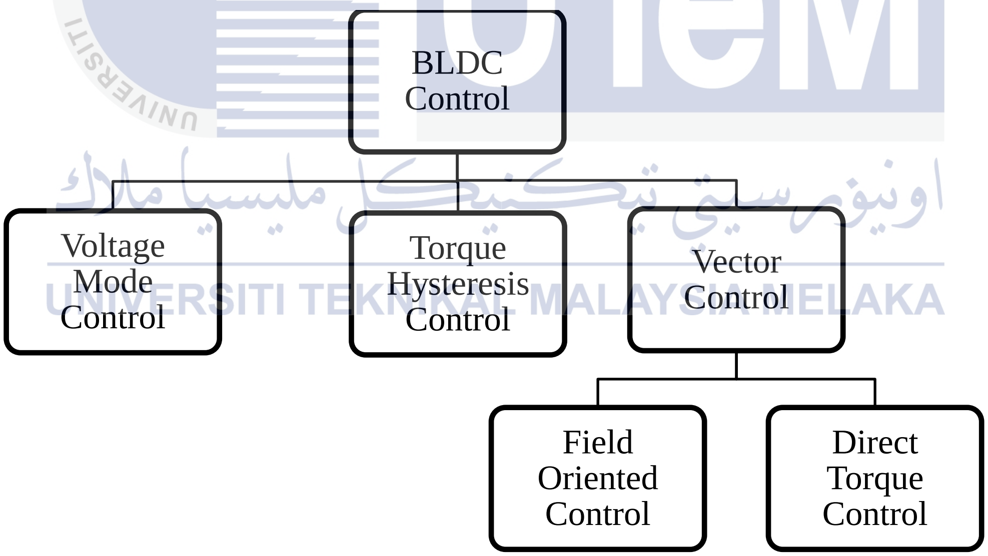

Figure 1.1 : BLDC Motor Control

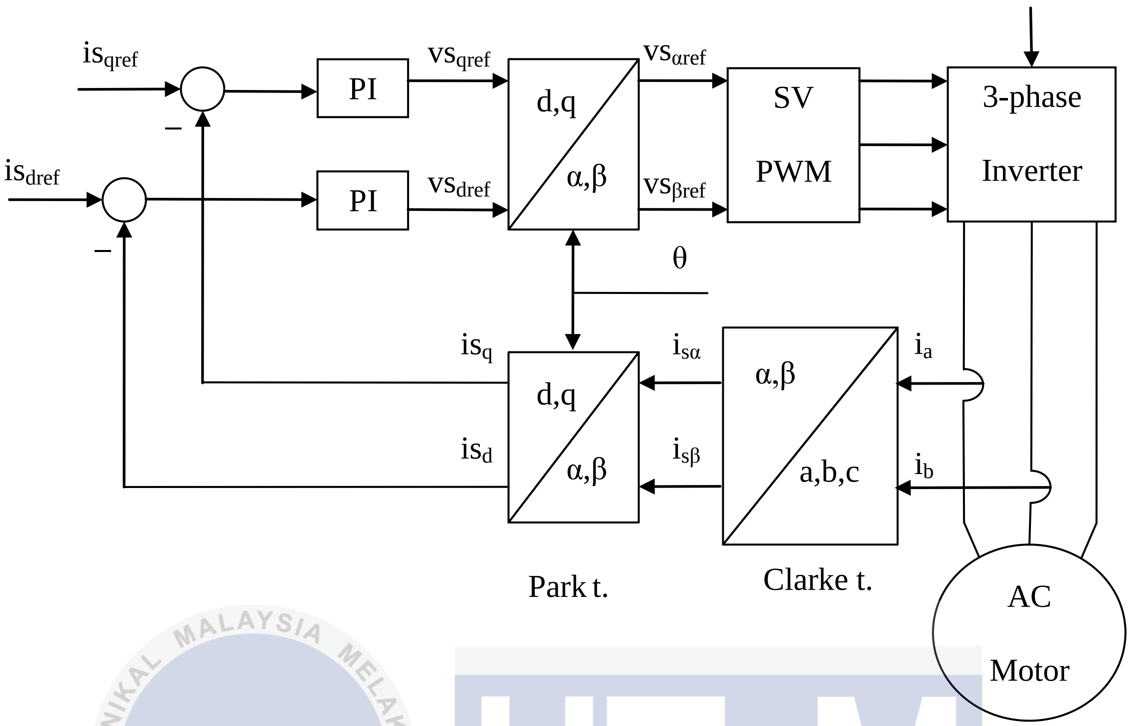

Figure 1.2: Basic Scheme of FOC of AC Motor

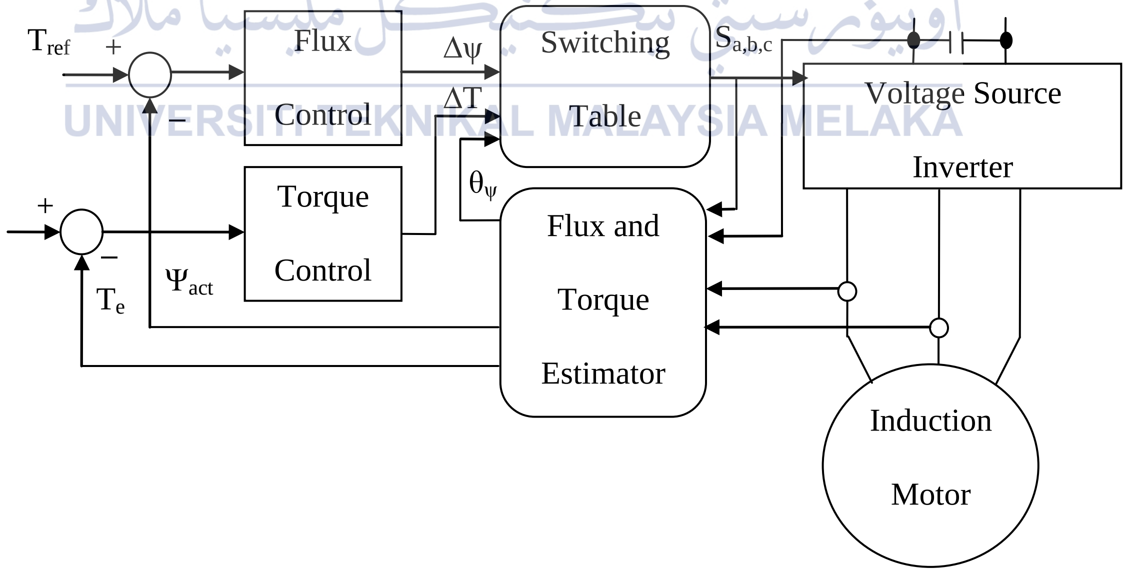

Figure 1.3: Basic Scheme of DTC of AC Motor

1.2 Significant of Research

Nowadays, the research on brushless DC motor (BLDC) drives has received enormous attention due to its excellent dynamic response, high efficiency, wide speed and high torque capability performances. It is known that the BLDC motor is the best option among other types of motor to replace the conventional brushed DC motor as it can achieve comparable DC motor performance however with less maintanence due to elimination of commutators and brushes in its construction. Moreover, the construction of BLDC motor allows the speed to operate for wide speed of range operations. However, the component used for the proposed topologies that is DTC of BLDC is lesser than the conventional (FOC). Thus, the implementation cost can be reduced.

In addition, it is well known that DTC has gained popularity because it offers excellent torque dynamic control. In DTC, it operates in two-phase conduction mode; where only two-phase produce switching at one time. As opposed to conventional THC method, the switching resulted in three-phase. It is engaged that the switching in DTC produces lower switching frequency and hence switching losses than that obtained in THC. However, the simulation results indicate otherwise. Meaning that, DTC produce higher switching frequency than THC. Thus, the significant of study is to prove that the switching frequency in THC is lower than DTC for every speed operating ranges.

1.3 Problem Statement

In the last two decade, several variations of BLDC drives have been proposed which includes the use of torque hysteresis controller (THC), and direct torque control (DTC). However, these methods have an essential difference in their implementation. The major problem in THC method is poor torque regulation performance. Current or torque ripple is not restricted within predefined hysteresis bandwidth. Simulation result in Figure 1.4 shows the torque or current regulation performance in THC.

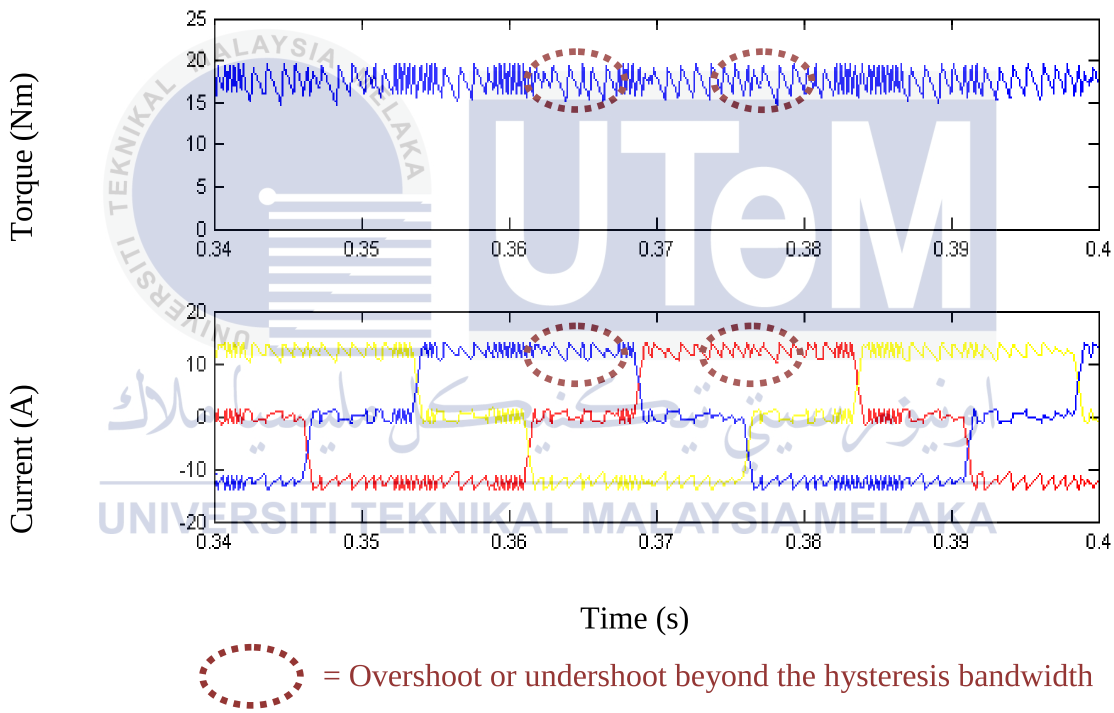

Figure 1.4 : Torque and Current Regulation Performance of THC

Besides, larger torque ripple in hysteresis controller both for DTC and THC need to be minimized ideally by reducing the bandwidth. However, reduce hysteresis bandwidth produce high frequencies since the regulation within bandwidth is more often. It shorten the time to travel (torque variation in bandwidth) from one band to another band. This phenomena lead to production of frequency exceed beyond the limitation of switching device known as IGBT. It affects the performance of the IGBT in terms of drop voltage, efficiency and the reliability of the switching device itself. Note that, it is desirable to provide high power efficiency of the BLDC drive system in order to prolong the energy battery source. The high switching frequencies caused in DTC is highlighted by using simulation results in Figure 1.5. It can be observed from right hand side of the figure (after zooming) that the switching frequency of DTC is high when small bandwidth is applied. It is analyzed by referring only to current in phase A. The torque hysteresis bandwidth (HB_T) is calculated in terms of percentage of peak current which is 12.714A and Table 1-1 below is the value of bandwidth for each percentage of current.

Table 1-1: Percentage and Torque Bandwidth in DTC

% of Peak Current	10% of Peak Current	25% of Peak Current
Torque Bandwidth (HB_T)	0.88998	2.22495

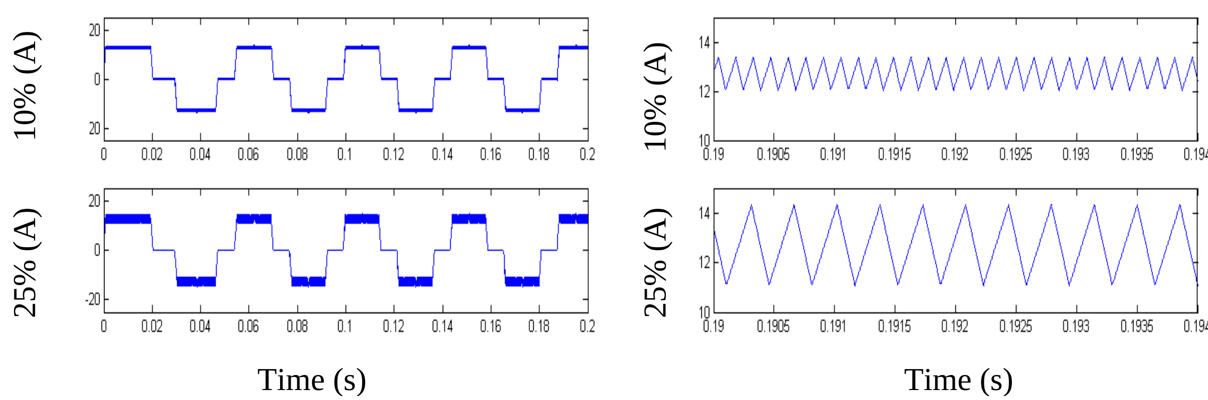

Figure 1.5 Switching Frequency Based on Hysteresis Bandwidth In DTC

1.4 Objective

The aims of this project are to:

i. model and simulate the Direct Torque Control (DTC) of Brushless DC Motor (BLDC) by using Matlab or Simulink.

ii. analyze and compare the switching frequency and torque/current control performances produced in Direct Torque Control (DTC) and Torque Hysteresis Control(THC) of Brushless DC Motor (BLDC) drive.

1.5 Scope of Research

This project mainly focuses on:

i. Mathematical modeling of BLDC motor.

ii. Modeling and simulation of DTC for BLDC motor using Matlab or Simulink.

iii. Evaluate the performances of DTC and THC of BLDC motor in terms of switching frequency and torque/current control.

1.6 Research Methodology

Upon completion of this research, several steps of process are made according to a sequence. All the steps or procedures in conducting this research are briefly explained in Chapter 3 with assistance of flowchart, milestone and Gantt chart that are given below.

1.6.1 Flowchart

Figure 1.6 shows the flow of activities conducted upon completion of this research based on the flowchart diagram. First, the information on BLDC motor and topologies of DTC and THC are gathered and studied to ensure the research to run smoothly. After gathering enough information on the proposed title, the simulation of DTC that involve two-level torque hysteresis controller and sector definition is constructed. By using the Matlab function, the look-up table can be developed and continue with the development of three phase VSI. For the estimator, it is simulated based on the equation that will further explain in Chapter 3. These simulations are fully constructed by using MATLAB/Simulink tools. Then, results from the simulation is captured and saved for further analysis. Finally, research report is written and compiled. All result, analysis and discussion on the data gathered will be presented in the report.

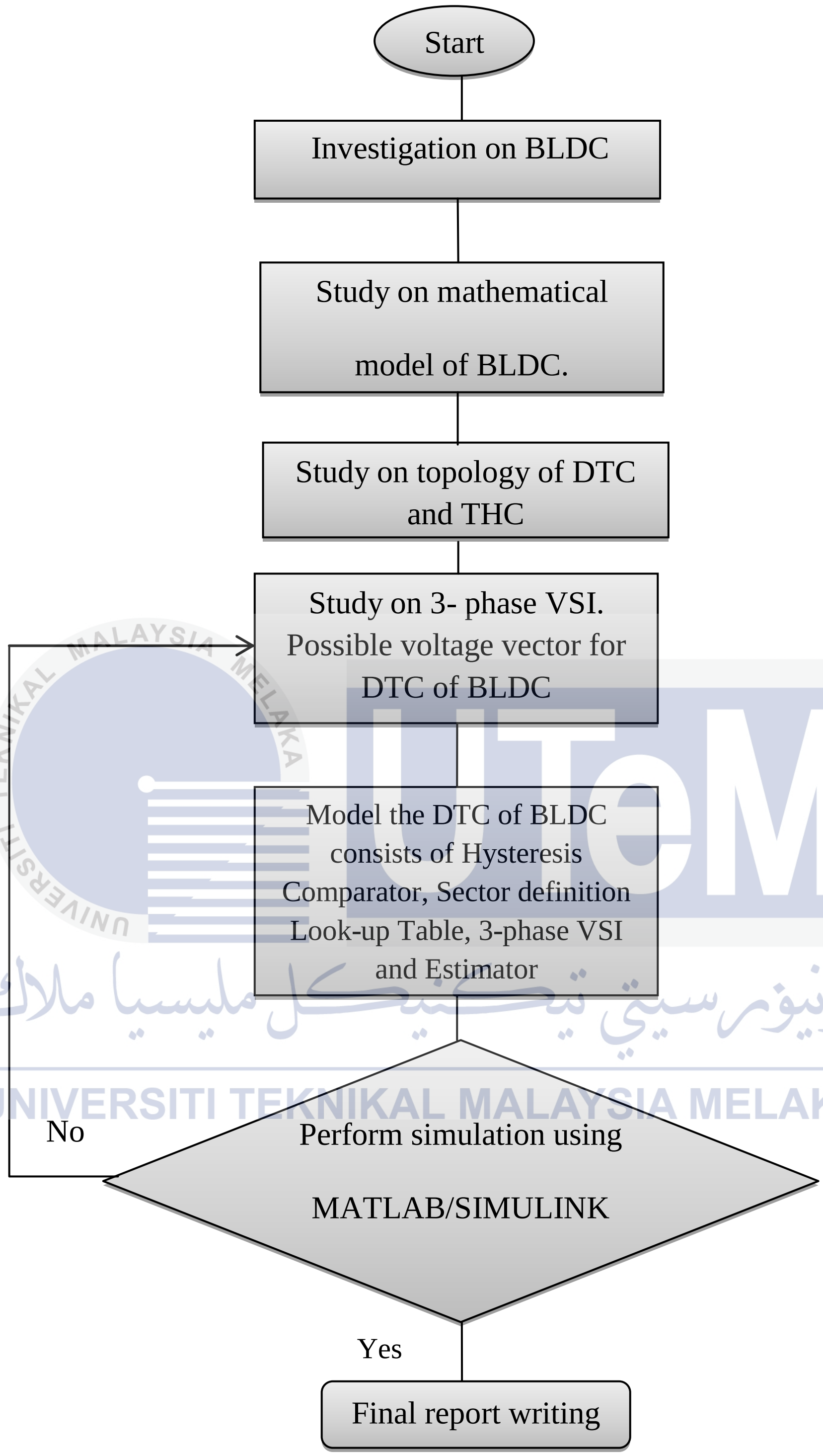

Figure 1.6: Flowchart of Research Methodology

1.6.2 Milestone

Below is the milestone stone set for this research. Table 1-2 shows the chart of activities conducted according to the month upon completion of this research. The research starts on September 2013. For the first three months, will be focused more on research of BLDC, DTC and THC consists of their topologies and control schemes. Two month is provided to study about the block diagram of DTC and Hall Effect signal in BLDC. Modelling of the DTC of BLDC consists of hysteresis comparator, Look-up Table, three- phase VSI and estimator. The time proposed for this process is approximately four months. Next, three months is used to conduct the overall simulation. The report writing is conducted along the way of the research process and no fix time is provided.

Table 1-2 : Gantt Chart of Research Methodology

Milestone	**Year**	**2013**				**2014**				
	Task	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**
1	Comprehensive investigation on BLDC Study on mathematical model of BLDC and the topology of DTC and THC	■	■	■						
2	Study on the block diagram of DTC and Hall Effect signal in BLDC		■	■						
3	Model the DTC of BLDC consists of hysteresis comparator , Look-up Table, VSI and Estimator			■	■	■	■			
4	Perform simulation by using MATLAB/SIMULINK						■	■	■	
5	Preparation of report and slide for presentation	■	■	■	■	■	■	■	■	■

1.7 Report Outline

This report consists of 5 chapters start with the introduction chapter that consists of brief explanation of the conventional vector control (FOC) and torque hysteresis control (THC) and how these two methods lead to the development of Direct Torque Control (DTC). In this chapter, it have been stated that this research is about DTC of Brushless DC Motor (BLDC) and why it is proposed. The objectives, scope and the significant of the research also presented in this chapter. Other chapters in this report are arranged as follow:

Chapter 2 discuss about the literature review of this research. This includes the explanation of basic DTC which is generally started with induction machine and production of torque and flux in DTC. The control schemes of DTC in induction motor will be described and theory about THC also can be seen in this chapter.

Chapter 3 discuss about the methodology of this research. All the methods used in accomplishing this research are explained. The first important things to know is the anatomy of BLDC and continue with mathematical modeling of BLDC, three-phase voltage source inverter (VSI) and construction of DTC of BLDC also will be discussed in details with the help of particular figure and block diagram.

Chapter 4 shows the overall results of these simulations from Matlab/Simulink and discussion about this proposed topic are stated in this chapter. Comparison between THC and DTC are analyzed in details.

Chapter 5 explains concludes about this research whether it achieves the desired objectives and able to solve the problems stated. Some recommendation has been written in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will discuss the literature review in order to gain enough information that can be use to complete the research. Data's include in this chapter are taken from thesis, books, journals, and any academic articles that are related to the research topic and will be clearly cited. Information about THC of BLDC is also highlighted in order to identify the problem occur in the THC itself. The basic DTC method of induction machine, the three-phase voltage source inverter (VSI) and its voltage space vectors are briefly explained. Besides, this section reviews the control of direct torque that can be performed by employing the suitable voltage vectors of eight possible switch configurations in the three-phase VSI. DTC will produce fast instantaneous torque and flux control when the decoupled control of stator torque and flux is obtained thus, yield simple control structure.

2.2 Torque Hysteresis Controller

The torque hysteresis controller (THC) is the technique to replace the conventional method that is voltage control in order to control torque and phase current of the BLDC machine. Due to the drawback of the voltage control, that has very high current overshoot, THC able to provide current protection. Meaning that, value of torque and current will stay within certain limits around with reference value [8-9].

This hysteresis control become one of the simplest closed-loop control schemes because the value of the controlled variable is forced to stay within certain limits around the reference value and. By using BLDC motor, with the help of THC, the excellent torque dynamic performance can be achieved. The structure of torque hysteresis controller can be shown in Figure 2.1. By controlling the three-phase motor current at its reference, the control of torque can be achieved, where it should be noted that the total production of torque is given as below.

$$T_{e,total} = T_{e,a} + T_{e,b} + T_{e,c} = k_{t,a} i_a + k_{t,b} i_b + k_{t,c} i_c \quad (2.1)$$

Where i_a, i_b, i_c = phase current

$k_{t,a}$, $k_{t,b}$, $k_{t,c}$ = torque constant (for each phase winding)

Two-level of hysteresis comparator is used to control each phase current. It is responsible to generate proper switching status in order to be fed into the inverter, either to increase or decrease the phase current such that its error (current ripple) is restricted within the hysteresis band [9].

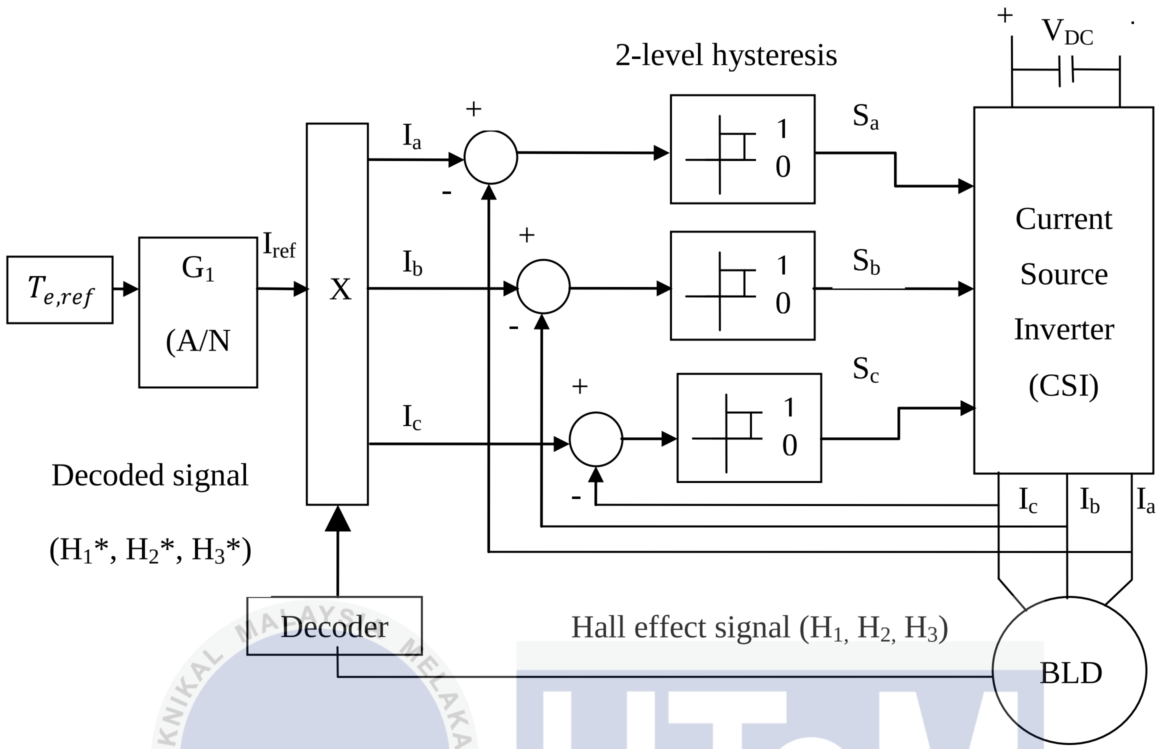

Figure 2.1: Structure of THC for BLDC Motor

2.3 Basic DTC method for Induction Motor

The DTC principle was introduced in the mid 1980s [10] and was proposed by Isao Takahashi in an Institute of Electrical Engineers of Japan (IEEJ) paper presented in September 1984 [13] and in an Institute of Electrical and Electronics Engineers (IEEE) paper published in late 1986 [13-14]. DTC was originally developed for induction machine drives. The sub-system of control system in DTC contain torque and flux hysteresis controller and optimal inverter switching logic. As the estimation of stator flux and motor torque depends on the modeling motor, precise machine model is also essential.

The desired locus of stator flux can be obtained by selecting the suitable inverter output voltage, [14]. For the rotor flux linkage, it can be assumed as constant in magnitude and in speed of rotation during short transients as it changes slowly compared to the stator flux linkage. This is due to the rotor time constant of induction machine that is usually large.

When the forward active voltage space vectors are applied, the stator flux linkage vector is moved away from the rotor flux linkage vector. The machine’s torque will increase due to the increament of torque angle. However, the torque angle reduced when the zero or backward active voltage space vector is applied. Hence, the torque is also reduced. It is clearly seen that by moving the stator flux linkage space vector to the required position, torque can be controlled directly while the stator flux linkage magnitude is kept within the hysteresis band. Thus, the controling of torque can be done quickly by selecting the suitable voltage vector. This is why the control scheme is called DTC [14].

For simpler explaination, the induction machine equations in terms of space vectors are written in the stator reference frame as below [22].

$$\bar{V}s = R_s \bar{\imath}_s + \frac{d\bar{\Psi}_s}{dt} \tag{2.2}$$

$$0 = R_r i_r + \frac{d\bar{\Psi}_s}{dt} - j\omega_r \bar{\Psi}_r \tag{2.3}$$

Where ω_r = rotor angular speed (rad)

$\bar{v}_s$ = stator voltage space vector

$\bar{\imath}_s$ = stator current space vector

$\bar{\imath}_r$ = rotor current space vector

$\bar{R}_s$ = stator resistance

$\bar{R}_r$ = rotor resistance

$\bar{\Psi}_s$ = stator flux linkages

$\bar{\Psi}_r$ = rotor flux linkages

Given that,

$$\bar{\Psi}_s = L_s \bar{\iota}_s + L_m \bar{\iota}_r \tag{2.4}$$

$$\bar{\Psi}_r = L_r \bar{\iota}_r + L_m \bar{\iota}_s \tag{2.5}$$

Where L_s and L_r respectively represent stator and rotor self-inductance.

DTC need set points of torque and flux as the inputs. The purpose of these two quantities are to establish closed loop control of the torque and flux. The torque and flux can be controlled separately by using hysteresis comparators [22]. The command values of flux, ψ_s and torque, T_e are both compared to the estimated value. However, there are no current controllers in DTC. The torque and flux controller are three-level hysteresis or two-level controllers in the case of induction machine. Based on the switching strategy, suitable voltage vector will be choosed and this requires information of hysteresis controllers together with the knowledge of the position of the stator flux linkage space vector. The important thing need to be highlight about DTC is the control system only need to know in which sector of the voltage space vector.

From the stator voltage equation, the stator flux can be directly calculated in the stator reference frame. It is given that [22]

$$\hat{\Psi}_{sd} = \int (V_{sd} - \hat{R}_s i_{sd}) dt \quad (2.6)$$

$$\hat{\Psi}_{sq} = \int (V_{sq} - \hat{R}_s i_{sq}) dt \quad (2.7)$$

Where $V_{sd}(i_{sd})$ = d -axis of stator voltage (current) components.

$V_{sq}(i_{sq})$ = q-axis of stator voltage (current) components.

$\hat{R}_s$ = estimated stator resistance.

Thus, the magnitude of stator flux is calculated as below.

$$|\hat{\Psi}| = \sqrt{\hat{\Psi}_{sd}^2 + \hat{\Psi}_{sq}^2} \quad (2.8)$$

As for the stator flux angle, ϕ is calculated by

$$\phi = \arctan\left(\frac{\hat{\Psi}_{sq}}{\hat{\Psi}_{sd}}\right) \quad (2.9)$$

Taking into consideration that $\bar{\hat{\Psi}}_s = \left|\bar{\hat{\Psi}}_s\right| e^{j\emptyset}$ and $\bar{\iota}_s = |\bar{\iota}_s| e^{j\alpha}$, where α is the angle of the stator current with respect to the direct-axis of the stator reference frame, the torque can be calculated in the following form below.

$$\hat{T}_e = \frac{3}{2}\frac{p}{2}\left|\bar{\hat{\Psi}}_s\right| |\bar{\iota}_s| \sin(\alpha - \emptyset) \quad (2.10)$$

Where p = number of pole

$(\alpha - \emptyset)$ = angle between the stator flux linkage and stator current space vector.

Last but not least, knowledge about the instantaneous position of stator flux should not be taken into consideration in DTC.

2.3.1.1 Basic Control Scheme of DTC of Induction Motor

In order to understand more about DTC, the three-phase voltage souce inverter (VSI) and its voltage space vectors are briefly explained in this chapter. From here, it can be shown clearly that the direct control of flux and torque can be performed by using appropriate voltage vectors of eight possible switching configuration in the three-phase VSI [12].

VSI are built in general with IGBTs or GTOs and for three-phase VSI, it contains six number of power switching devices that can transform DC link voltage to the desired AC voltage. Figure 2.2 shows the three-phase VSI that is connected to the Y windings of induction machine. It is important to remember that the selector switch for each leg or phase of VSI represent the upper and lower switches which are complement to each other. Meaning that, when the upper switch of the leg is ON and the lower switch is OFF, the switching state of each phase (S_a,S_b, S_c) equals to 1. Other than that, the switching state equal to 0. From Figure 2.3, it can be seen that combination of switching states in the VSI produce eight possible switching configuration which represent the eight different voltage space vector [14].

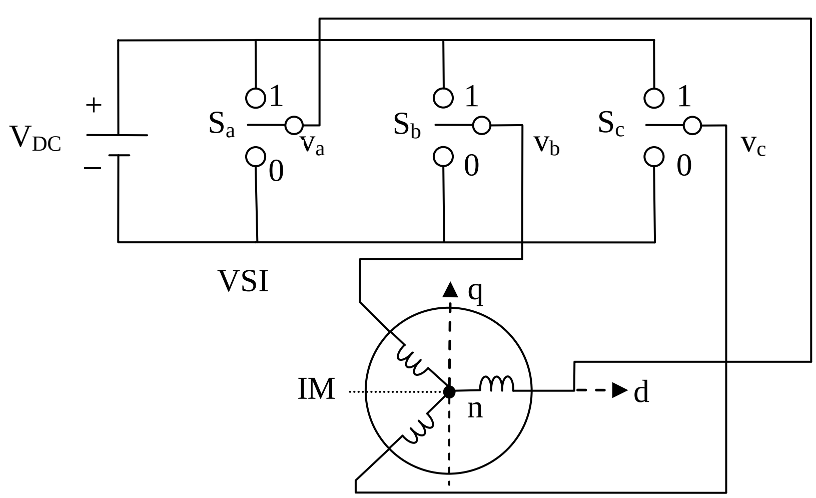

Figure 2.2: Schematic diagram of VSI [14]

In three-phase VSI, it contains six non-zero space phasors. Besides, located at the origin of the voltage plane, there are two zero voltage vectors [10] as in Figure 2.3 below.

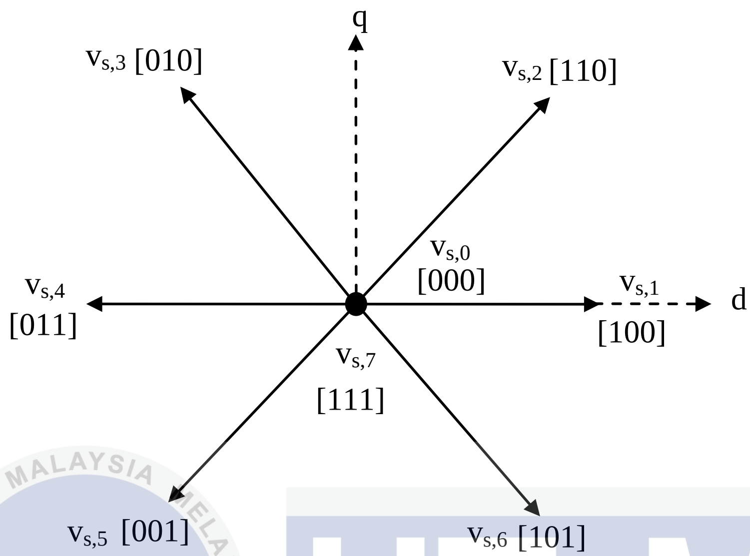

Figure 2.3: Voltage Vectors Based on Switching Configuration in VSI [14].

In DTC drives, it is important to maintain the stator flux and torque error within prescribed hysteresis bands. The inverter switching frequency will be affected by the size of the hysteresis band. Generally, the larger the hysteresis band, the lower the switching frequency. Thus, the response of drive is more efficient [10]. Basic control scheme of DTC of induction motor for torque mode operation is shown in Figure 2.4.

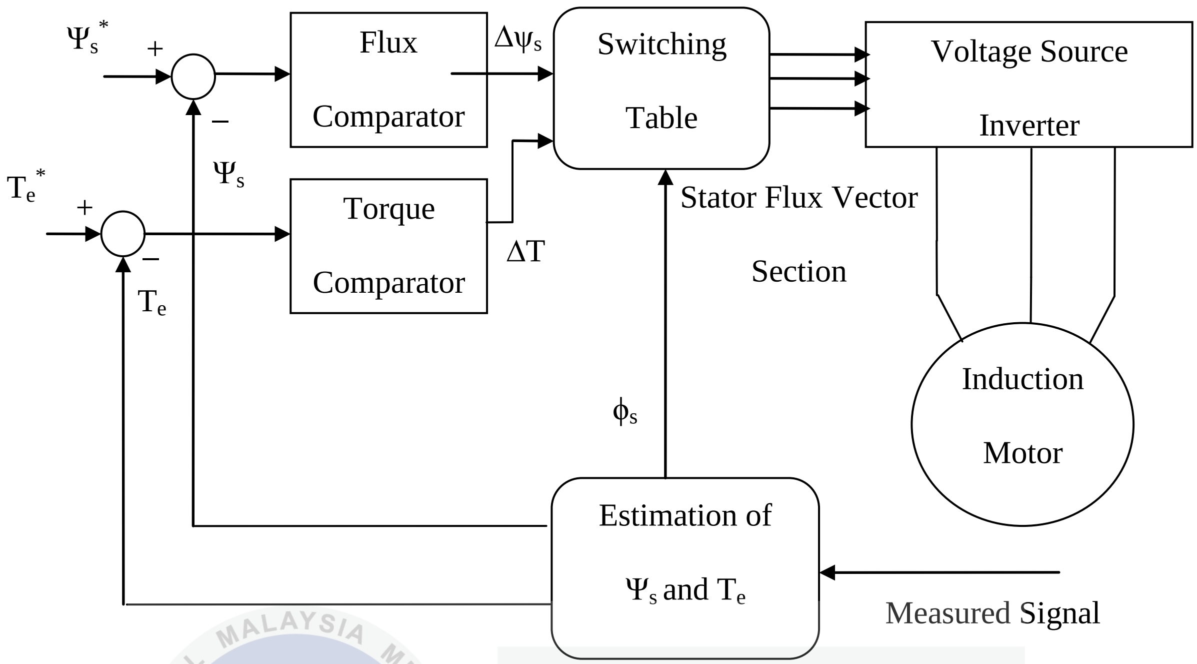

Figure 2.4 : Control Scheme of DTC of Induction Motor

In this scheme, the command values of flux, Ψ_s and torque T_e are compared to the estimated values respectively. In the case of flux, the errors are fed to a two-level comparator and produce flux error status, while three-level in the case of torque results in torque error status. A lookup table of optimum voltage vectors as proposed in [1] is develops by using the information from the output of the comparators and the stator flux angle in order to determine the appropriate voltage vectors. Table 2-1 shows voltage vectors lookup table for DTC. Figure 2.5 illustrate the sector of the stator flux that is divided into six sectors. It indicates that, the suitable voltage vector (taken from the table of optimum voltage vectors) should be chosen in a respective sector, either to increase stator flux or to decrease stator flux and either to increase torque or to reduce torque [21]. The selection of voltage vector is made to limit the errors of the stator flux and torque within their particular hysteresis bands. As a result, the highest efficiency and fastest torque response at every instant can be obtained.

In Figure 2.5, the position of flux is divided equally into six sectors. Based on the definition of the sectors, by using two possible active voltage vectors, either to increase or decrease the flux, the circular flux control can be performed [10]. The examples are illustrated in Figure 2.5 where it show how the flux is increase and decrease with the use of voltage vectors $V_{s,2}$ and $V_{s,3}$ when it is positioned in Sector I and the flux is increase and decrease with the use of voltage vectors $V_{s,3}$ and $V_{s,4}$ when it lies in Sector II and other voltage vector are selected for other sector.

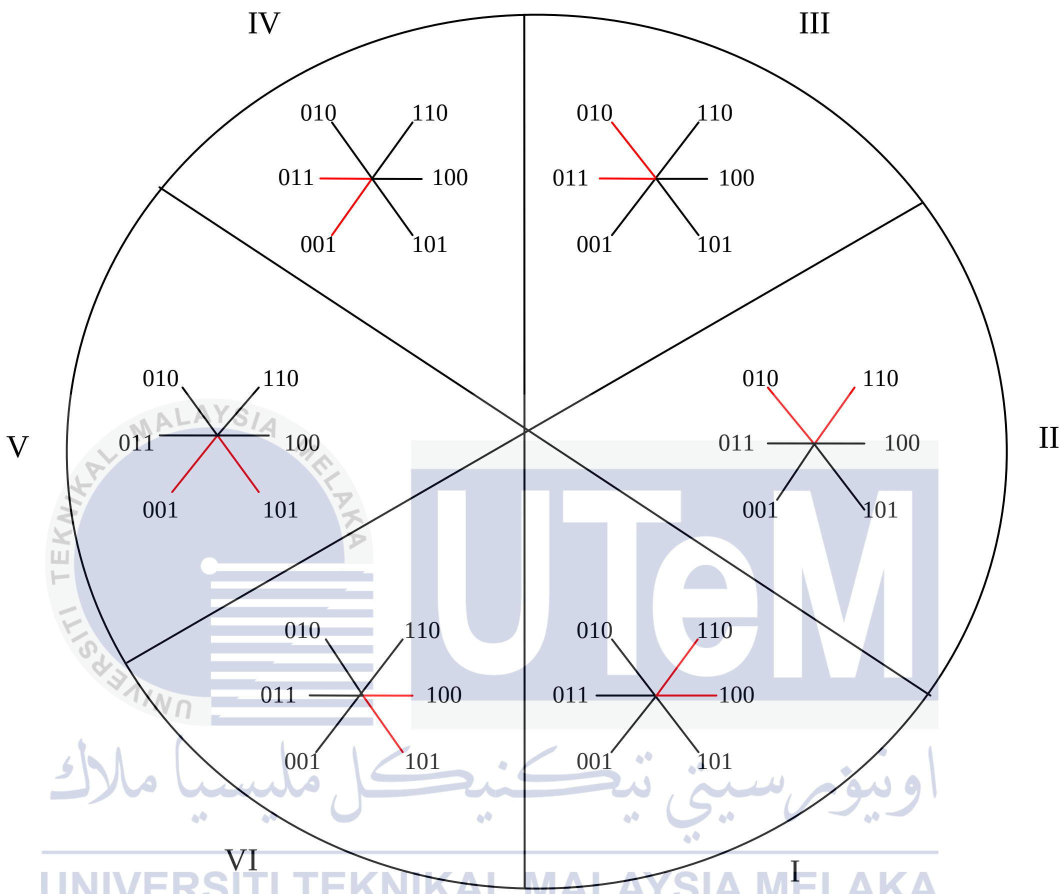

Figure 2.5: Six Sectors of Stator Flux Plane

Table 2-1:Voltage Vectors Look-up Table for IM

Stator flux error status, Ψ_s^+	Torque error status, T_{stat}	Sector I	Sector II	Sector III	Sector IV	Sector V	Sector VI
1	1	[100]	[110]	[010]	[011]	[001]	[101]
	0	[000]	[111]	[000]	[111]	[000]	[111]
	-1	[001]	[101]	[100]	[110]	[010]	[011]
0	1	[110]	[010]	[011]	[001]	[101]	[100]
	0	[111]	[000]	[111]	[000]	[111]	[000]
	-1	[011]	[001]	[101]	[100]	[110]	[010]

2.3.1.2 Torque and Flux Control in DTC of Induction Motor

In DTC, the output torque and flux is controlled by limiting its error within prescribed hysteresis band. As shown on Figure 2.6 the estimated stator flux is subtracted from the corresponding reference value to obtain the error, which is then fed to the hysteresis comparator.

i. φstat = 1 occur when the stator flux needs to be decreased or when the status flux error touches the lower band.

ii. φ_{stat} = 0 occur when stator flux need to be increased or when the flux error touch the upper band.

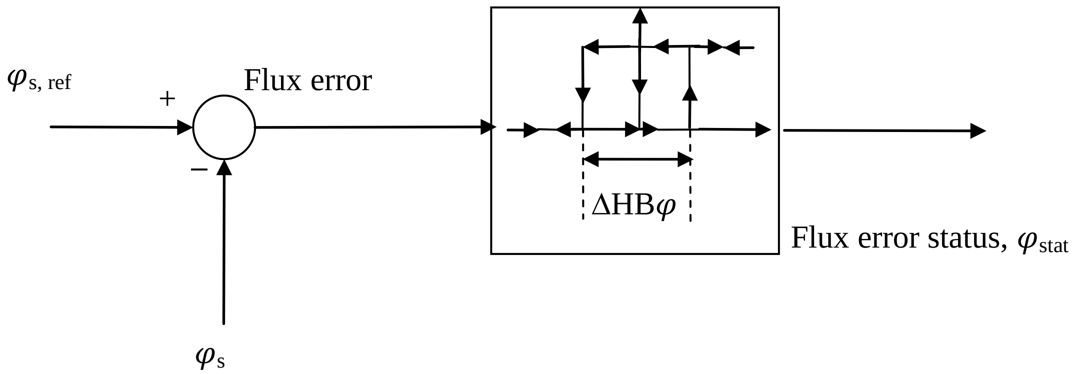

Figure 2.6: Control of Flux Magnitude Using Two-level Hysteresis Comparator

As for the torque, the three-level hysteresis comparator is employed and shown in Figure 2.7 [14].

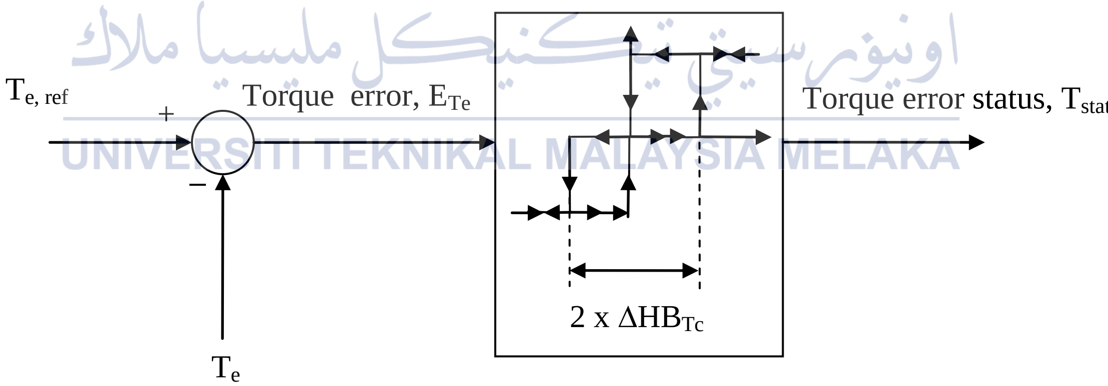

Figure 2.7 : Control of Torque using a Three-level Hysteresis Comparator

The output of the comparator named as torque error status, T_{stat} generate a digitized signal which can be either 1,0, or -1. Concentrate on the same quadrant (forward motoring and forward braking), the torque error status that determine the suitable voltage vectors can be classified in the condition below:

iii. T_{stat} = 1 occur when the actual torque needs to be increased or when the torque error touches the upper band. In this condition, active forward voltage vector is selected.

iv. T_{stat} = 0 occur when actual torque need to be decreased or when the torque error touch the middle band which means that the torque is satisfied to its demand. Thus, zero voltage vectors is selected.

v. T_{stat} = -1 occur when the actual torque need to be decreased or when the torque error touches the lower band. In this condition, active reverse voltage vector is selected.

2.4 Related Previous Work

Since DTC of BLDC have been a popular issue in this recent years, there are several variations of DTC method for BLDC motor have been proposed by the researchers. There are various look- up table that involve in two-phase conduction scheme. This related previous work will be explained below.

2.4.1 Variations of DTC methods in Two-Phase Conduction Mode for BLDC motor

By referring to [11], DTC of BLDC is operating in two-phase conduction mode which means that only two phases conduct at any instant of time. It is due to just control torque by intentionally keeping the stator flux linkage amplitude almost constant by eliminating the flux control. By neglecting the flux control, fewer algorithms are required for the proposed the control scheme. Thus, torque is controlled while the stator flux linkage is kept constant on purpose. Furthermore, simulations presented in [11] shows that there is some disadvantages by using zero inverter voltage space vector in order to decrease the electromagnetic torque. For example, zero inverter voltage space vectors can produce larger spikes frequently on the phase voltage. Thus, increase the switching losses that can totally damage the motor bearing. The flux error in the look-up table (voltage vector selection) is always preferred as zero in order to solve this problem. Only the torque error is used depends on the error level of the actual torque from the reference torque. If the reference torque is larger than the actual torque within the hysteresis band, the torque error is defined as “1” or “-1”. Table 2-2 shows that new simple two-phase inverter voltage space vector look-up table is develop.

Table 2-2 : Look-up table for two-phase voltage vector for BLDC

ψ	$\mathcal{T}$	θ					
		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
1	1	V_1(100001)	V_2(001001	V_3(011000)	V_4(010010)	V_5(000110)	V_6(100100)
	-1	V_6(100100)	V_1(100001)	V_2(001001	V_3(011000)	V_4(010010)	V_5(000110)
0	***1***	***V_2(001001***	***V_3(011000)***	***V_4(010010)***	***V_5(000110)***	***V_6(100100)***	***V_1(100001)***
	-1	***V_5(000110)***	***V_6(100100)***	***V_1(100001)***	***V_2(001001***	***V_3(011000)***	***V_4(010010)***
-1	1	V_3(011000)	V_4(010010)	V_5(000110)	V_6(100100)	V_1(100001)	V_2(001001
	-1	V_4(010010)	V_5(000110)	V_6(100100)	V_1(100001)	V_2(001001	V_3(011000)

Note : The bold italic area is used in the proposed DTC of a BLDC motor drive [4].

Another look-up selection table will be presented below are referred to [12]. In each sector, only one non-zero voltage space vector and a zero voltage vector are used to control the increase (T=1) or decrease (T = 0) of torque if the stator flux linkage (ϕ = 0). It is noted that during any 60º electrical period only two-phases are triggered and controlled in BLDC drive. However, when (ϕ = 1), the non-zero voltage space vector is used to increase the flux linkage. As for (ϕ = -1), the non-zero voltage space vector are used to decrease the stator flux linkage. However, most look-up table in DTC of BLDC in two-phase conduction mode highlighted that the flux is consider zero or eliminated in order to easily control the torque.

Table 2-3 : Switching Table for DTC of BLDC Drive

T	ϕ	Sector					
		I	II	III	IV	V	VI
1	1	V_1(100001)	V_2(001001	V_3(011000)	V_4(010010)	V_5(000110)	V_6(100100)
	0	***V_2(001001***	***V_3(011000)***	***V_4(010010)***	***V_5(000110)***	***V_6(100100)***	***V_1(100001)***
	-1	V_3(011000)	V_4(010010)	V_5(000110)	V_6(100100)	V_1(100001)	V_2(001001
0	1	V_1(100001)	V_2(001001	V_3(011000)	V_4(010010)	V_5(000110)	V_6(100100)
	0	***V_5(000110)***	***V_6(100100)***	***V_1(100001)***	***V_2(001001***	***V_3(011000)***	***V_4(010010)***
	-1	V_3(011000)	V_4(010010)	V_3(011000)	V_4(010010)	V_5(000110)	V_6(100100)

2.5 Summary of Review

This chapter discussed about basic DTC method. The topologies of DTC of induction machine along with the decoupled control of flux and torque in DTC-hysteresis based induction machine also been explained. From the explanations, shows that it is possible to control flux and torque directly based on the appropriate voltage vector. Thus, this decoupling results in a fast instantaneous control of flux and torque. By making the flux is constant on purpose only the torque needs to be considered. In this project of DTC of BLDC motor drives, the look-up table is not proposed but, with the help of Table 2-2, the selected sector can be obtained. This table is easily to understand. It can be seen that in DTC of BLDC with two-phase conduction mode, the flux error in the voltage vector selection table is always chosen as zero and only torque error is used depends on the error level of actual torque from the reference torque. If the torque reference is bigger than torque actual within the hysteresis band, the torque error is defined as 1 or else it is -1 as shown in Table 2-2.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Implementation of DTC method will be carried out based on the investigation about various control strategy of BLDC motor. The first thing to look at is the anatomy and the mathematical modeling of BLDC motor. Electrical and mechanical equations are important in order to model BLDC motor. Besides, research on switching losses is needed to propose an optimal switching strategy of BLDC motor by using suitable voltage vector. This chapter will also give brief explanations of the modeling and simulation of DTC of BLDC. Last but not least, the simulation MATLAB/Simulink in are presented along with details explanation.

3.2 Anatomy of BLDC

Brushless DC Motor fed by two-phase conduction mode has several benefits that is, higher torque or current ratio and higher power. Compared to three-phase feeding permanent magnet synchronous motor (PMSM), this two-phase conduction scheme is less expensive due to concentrated windings which shorten the end windings [23].

Figure 3.1 shows the illustration of BLDC motor construction. It is constructed with a permanent magnet rotor and wire wound stator poles. In this case, the rotor consist only two poles, north and south. Noted that electrical energy is converted to mechanical energy by the magnetic attractive forces between the permanent magnet rotor and a rotating magnetic field induced in the wound stator poles [16]. In this example, it can be seen that there are three electromagnetic circuits connected at a common point. Each electromagnetic circuit is split in the center, thus permitting the permanent magnet rotor to move in the middle of the induced magnetic field.

The main purpose of BLDC commutation is to sense the rotor position, and then energize the phases that will produce the most amount of torque.

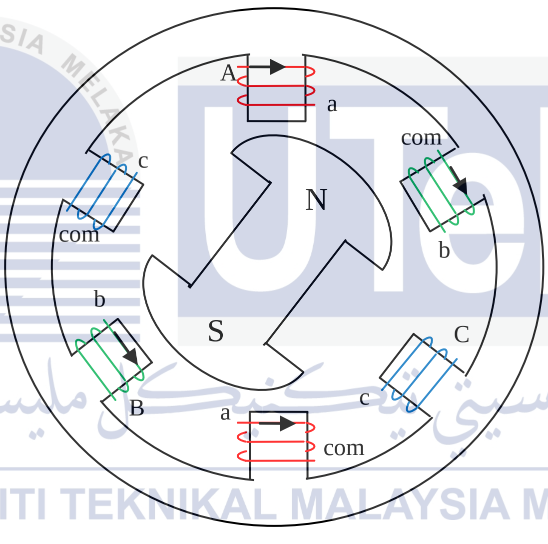

Figure 3.1 : BLDC motor Construction

Figure 3.2 shows the six step commutation of BLDC. Each step is equivalent to 60 electrical degrees. Six step results in 360 electrical degrees which indicate as one electrical revolution. However, when the rotor is 120 degrees from alignment with the corresponding stator magnetic field the appropriate stator current path is activated and then deactivated when the rotor is 60 degrees from alignment [17]. Those arrows in the winding show the direction of current flows through the motor windings.

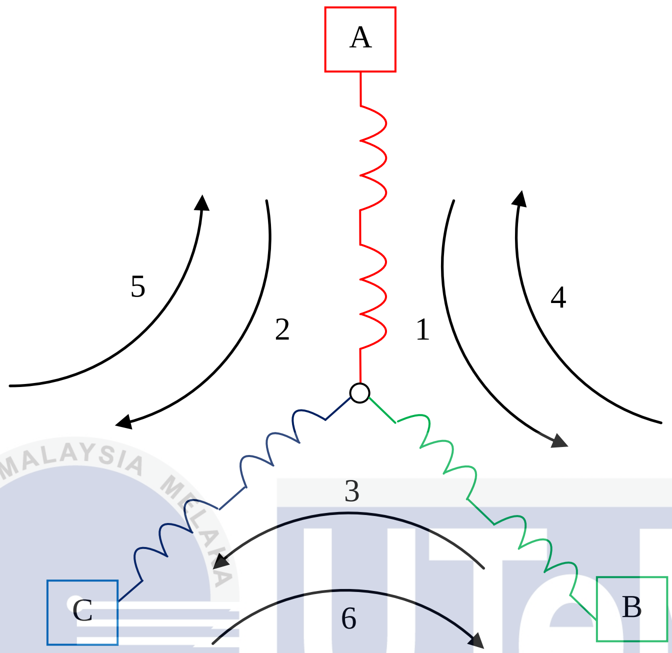

Figure 3.2 : Six-step Commutation of BLDC

3.2.1 Sensored BLDC Control using Hall Effect Sensor

In most BLDC control applications, Hall Effect sensor is usually used as the position sensor to determine the rotor position. These sensors are located in the motor housing and are offset from each other by 120 electrical degrees so that each sensor output is aligning with one of the electromagnetic circuit. Figure 3.3 – Figure 3.8 shows the six step commutation for sensored BLDC motor in anti-clockwise rotation.

Motor will turns when the current passed through motor windings. For example, Step 1 in Figure 3.3 shows that a positive potential is applied to the (A) lead while in (B) lead negative potential is applied. Currents flow through this windings will generates magnetic field (North and South) in the stator. Then, the rotor turns in order for the North Pole in the rotor to align with the magnetic south generated from the stator. Similarly, the South Pole in the rotor align with the magnetic north generated in the stator. The next other steps hold on the same concept but with different current flow [18].

Figure 3.3 and Table 3-1 below shows the North pole (rotor) only triggered Ha. Since the North pole is not facing the Hb and the rotor started to leave the Hc sensor, it does not triggered. Thus Hb and Hc is considered as 0.

Step 1 : Red (A) winding is driven positive

Green (B) winding is driven negative

Blue (C) winding is not driven

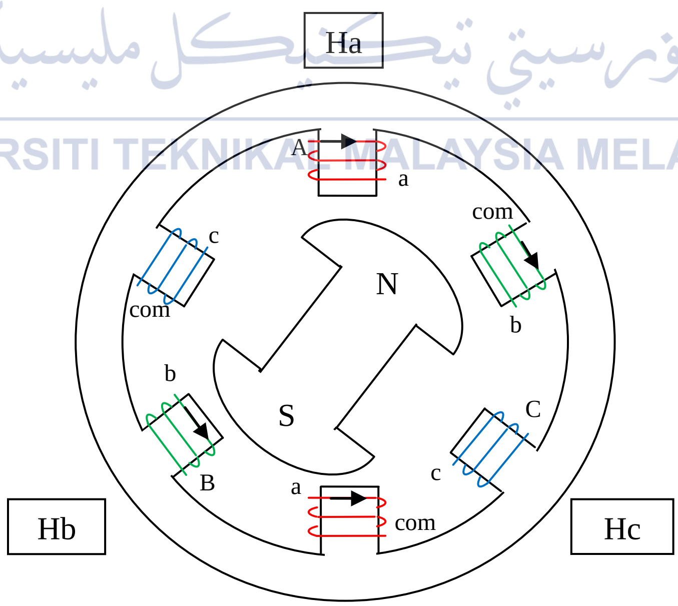

Figure 3.3 : Commutation Process including Hall Effect in Step 1

Table 3-1: Hall Effect Signal in Step 1

Ha	Hb	Hc
1	0	0

Figure 3.4 and Table 3-2 shows the North pole (rotor) triggered Ha. Since the North pole start to enter the position of the Hb sensor, it is also triggered. As for the Hc sensor, it is considered as 0 since it facing the South pole.

Step 2 : Red (A)winding remains positive

Blue (C) winding is driven negative

Green (B) winding is not driven

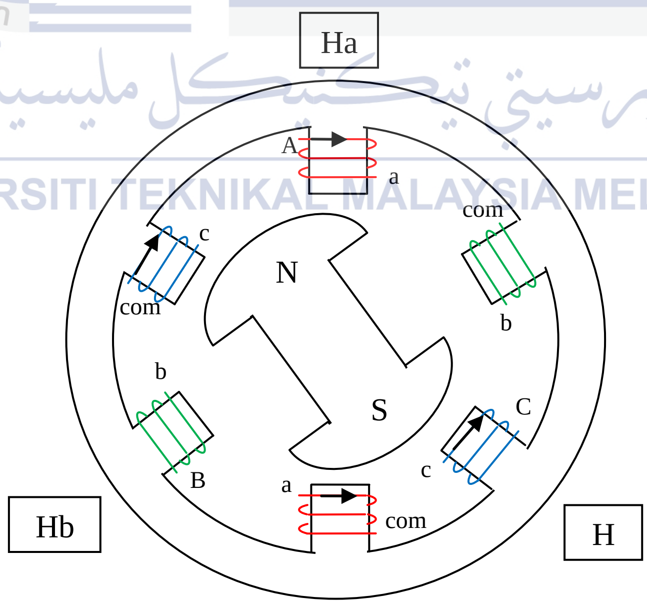

Figure 3.4 : Commutation Process including Hall Effect in Step 2

Table 3-2 : Hall Effect Signal in Step 2

Ha	Hb	Hc
1	1	0

Figure 3.5 and Table 3-3 shows the North pole (rotor) only triggered Hb. Since the North pole is not facing the Hc and the rotor started to leave the Ha sensor, it does not triggered. Thus Ha and Hc is considered as 0.

Step 3 : Green (B) winding is driven positive

Blue (C) winding is driven negative

Red (A) winding is not driven

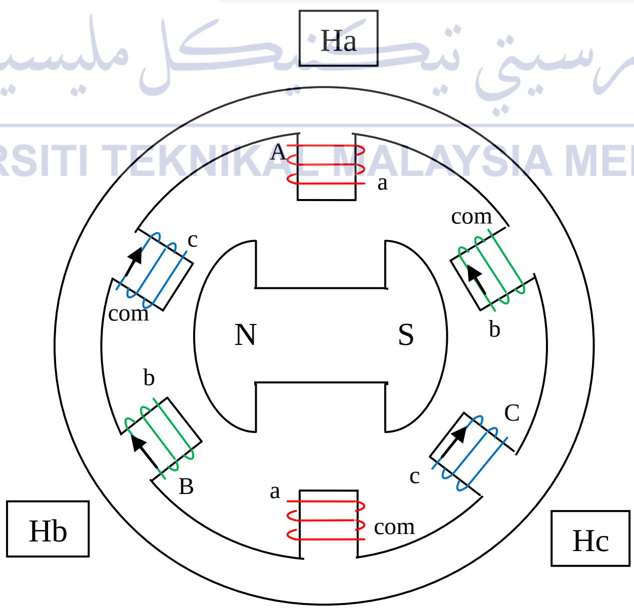

Figure 3.5 : Commutation Process including Hall Effect in Step 3

Table 3-3 : Hall Effect Signal in Step 3

Ha	Hb	Hc
0	1	0

Figure 3.6 and Table 3-4 shows the North pole (rotor) triggered Hb. Since the North pole start to enter the position of the Hc sensor, it is also triggered. As for the Ha sensor, it is considered as 0 since it facing the South pole.

Step 4 : Green (B) winding is driven positive

Red (A) winding is driven negative

Blue (C) winding is not driven

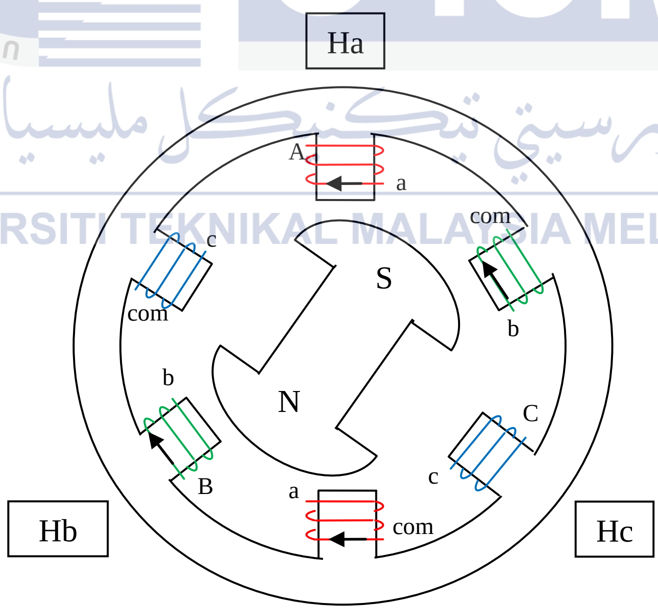

Figure 3.6 : Commutation Process including Hall Effect in Step 4

Table 3-4: Hall Effect Signal in Step 4

Ha	Hb	Hc
0	1	1

Figure 3.7 and Table 3-5 shows the North pole (rotor) only triggered Hc. Since the North pole is not facing the Ha and the rotor started to leave the Hb sensor, it does not triggered. Thus Ha and Hb is considered as 0.

Step 5 : Blue (C) winding is driven positive

Red (A) winding is driven negative

Green (B) winding is not driven

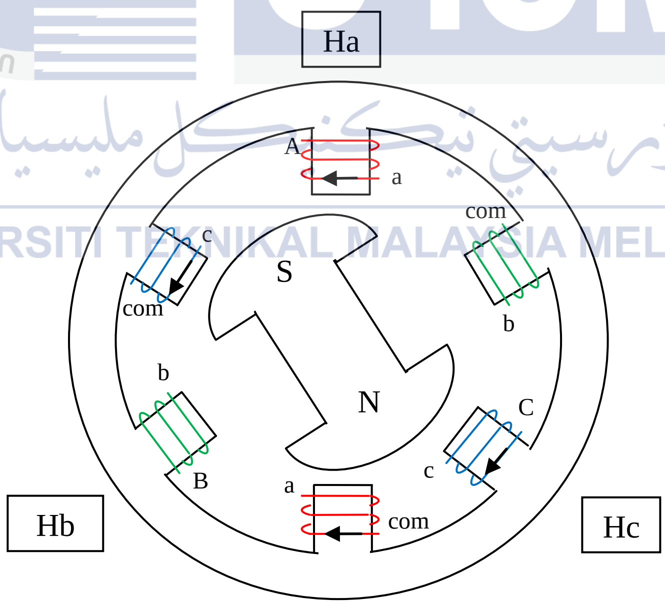

Figure 3.7 : Commutation Process including Hall Effect in Step 5

Table 3-5 : Hall Effect Signal in Step 5

Ha	Hb	Hc
0	0	1

Figure 3.8 and Table 3-6 shows the North pole (rotor) triggered Hc. Since the North pole start to enter the position of the Ha sensor, it is also triggered. As for the Hb sensor, it is considered as 0 since it facing the South pole.

Step 6 : Blue (C) winding is driven positive

Green (B) winding is driven negative

Red (A) winding is not driven

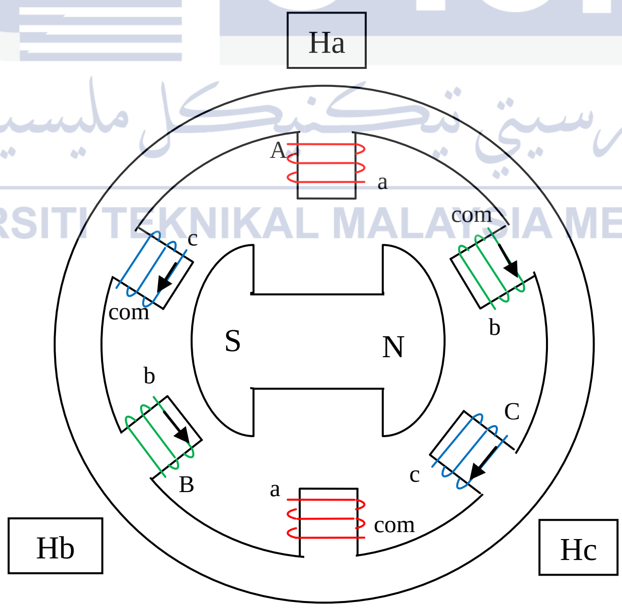

Figure 3.8 : Commutation Process including Hall Effect in Step 6

Table 3-6 : Hall Effect Signal in Step 6

Ha	Hb	Hc
1	0	1

Figure 3.9 below shows the relationship between the sensor outputs and the sector in which the position of rotor is located. The switching states are also shown in order to control the current flow through the motor [19].

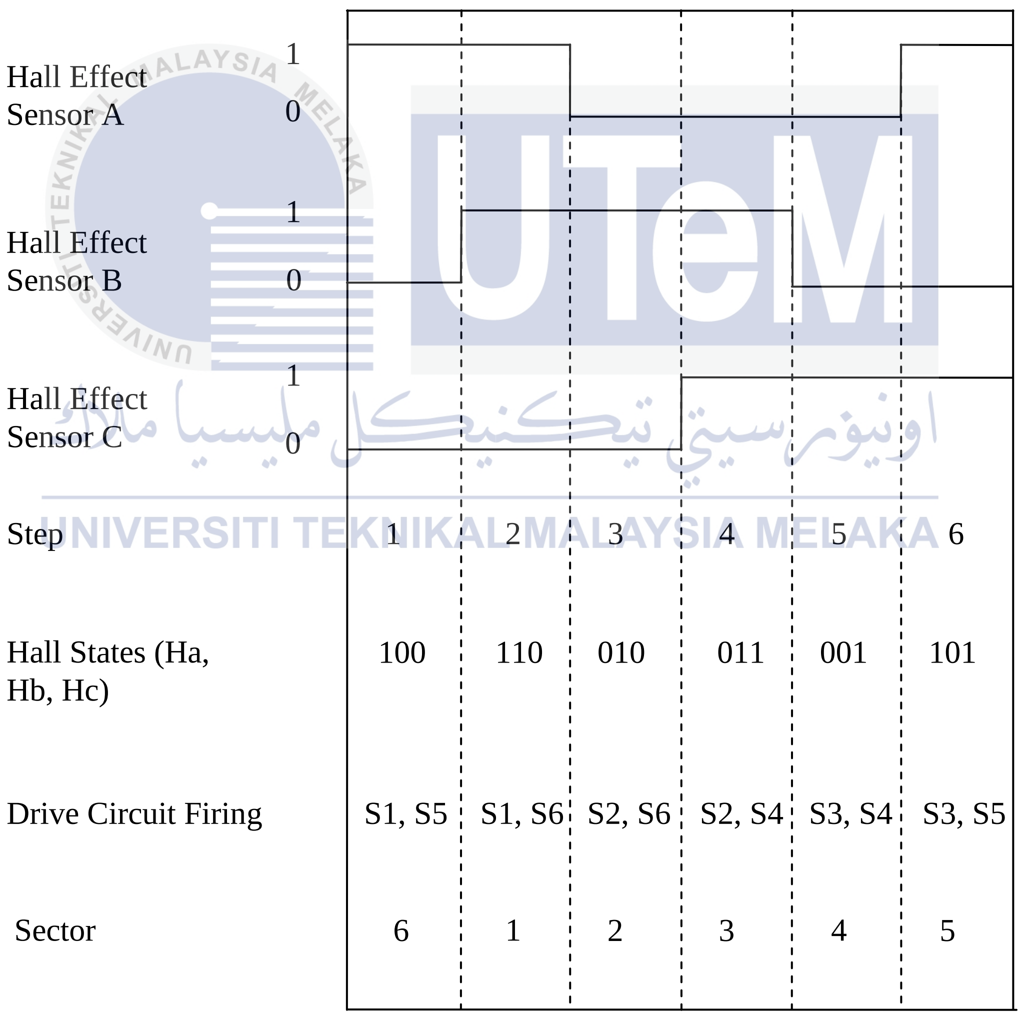

Figure 3.9: **Sensored Control**

Figure 3.10 shows an inverter circuit connected to BLDC motor. Each motor lead is connected to a high and low-side switch. The relation between sector and the switch states is shown by the drive circuit firing in Figure 3.9 above.

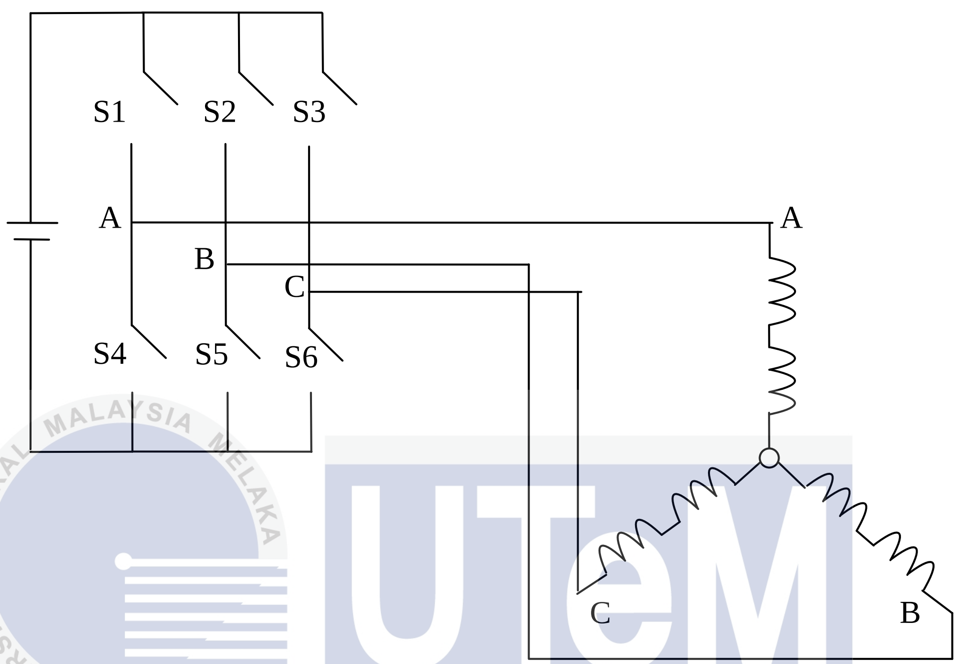

Figure 3.10 : BLDC Drive Circuit

3.3 Mathematical Modeling of BLDC motor

A precise model for the BLDC motor is required to evaluate the functionality of any controller. Modeling of BLDC involves two equations which is electrical and mechanical equations [4,5,6]. The derivation is similar to DC machine where it consists of two equivalent circuits. However, the construction of BLDC motor is different from DC machine because it has three phase windings at stator (with n number of pole). Moreover, the rotor is equipped with permanent magnet containing north and south poles and is positioned at the centre of the motor. In BLDC motor, permanent magnet will be powered by electrical current in order to move the motor. No physical commutator is necessary thus; BLDC motor must be electronically commutated.

The first step in developing any machine model is to consider the derivation of the characteristic equations that refer to its dynamic and steady- state behavior. Basic circuit analysis was used to attain electrical equations for BLDC machine. Figure 3.11 represents BLDC machine equivalent circuit. Thus, per-phase voltages are shown in Equation 3.1 [15].

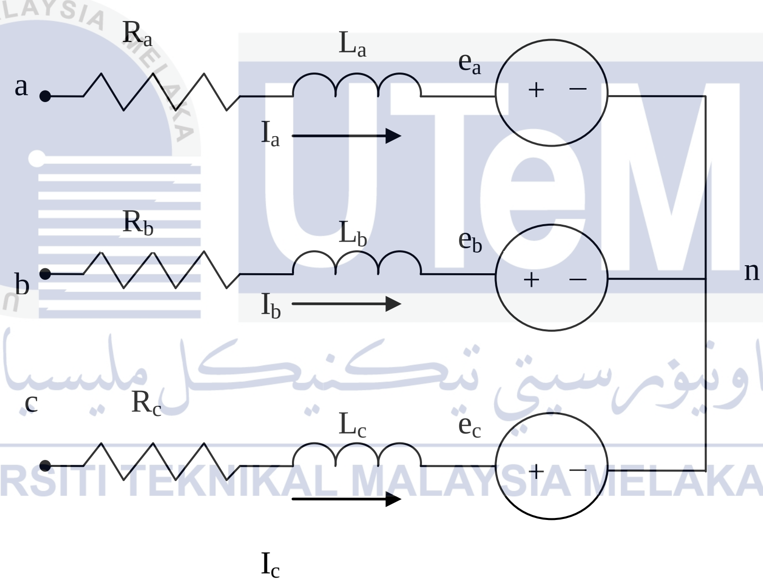

Figure 3.11 : Three Phase BLDC Machine Equivalent Circuit

Electrical equation (phase k = a,b,c) :

$$Vkn(t) = inRn + Ln\,\frac{dik}{dt}\,t + en(t) \tag{3.1}$$

Where, $Vkn(t)$ = n - phase voltage

$ik(t)$ = n - phase current

$ek(t)$ = n - phase back – emf voltage

Rk = n - phase resistance

Lk = n - phase inductance

Besides electrical equation, mechanical equation needs to be considered in modeling BLDC motor. In order to describe the machine’s angular motion, see Figure 3.12 and Equation 3.2. [15]

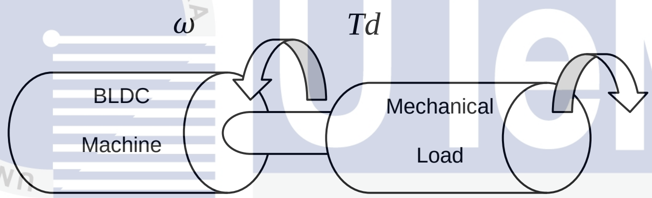

Figure 3.12 : BLDC Mechanical Coupling

Mechanical Equation:

$$Td(t) = \omega(t)b + J\frac{d\omega}{dt} + Tl(t) \quad (3.2)$$

Where, $Td(t)$ = develop torque

$\omega\,(t)$ = rotor angular frequency

b = viscous friction

J = moment of inertia

Tl = load torque

Both Equation 3.1 and Equation 3.2 are coupled by the developed electromagnetic torque (Td) and the back-emf (e_{phase}) in terms of current and speed. Refer to Equation 3.3 and Equation 3.4.

$$Td = k_{t\text{-}a}\, i_a + k_{t\text{-}b}\, i_b + k_{t\text{-}c}\, i_c \tag{3.3}$$

$$E_a = k_e\, \omega(t) \tag{3.4}$$

Where, $k_{t\text{-}n}$ = per-phase torque sensitivity

$K_{e\text{-}n}$ = per-phase back-emf

It should noted that the torque sensitivity is a function of rotor position and phase current while the back-emf is a function of rotor angular position and rotor angular speed. After that, Equations 3.1 and 3.2 are transformed into Laplace transform (see Equation 3.5, 3.6, 3.7, and 3.8) including the relations of e_a and Td. These equations are used to construct the block diagram shown in Figure 3.13 [15].

$$V_{an}(s) = I_a(s)\, R_a + I_a(s)\, L_a + k_{e,a}\, \omega\, (s) \tag{3.5}$$

$$V_{bn}(s) = I_b(s)\, R_b + I_b(s)\, L_b + k_{e,b}\, \omega\, (s) \tag{3.6}$$

$$V_{cn}(s) = I_c(s)\, R_c + I_c(s)\, L_c + k_{e,c}\, \omega\, (s) \tag{3.7}$$

$$K_{t,a}\, I_a(s) + k_{t,b} I_b(s) + k_{t,c}\, I_c(s) = \omega(s)\, b + \omega\, (s)\, sJ + Tl\, (s) \tag{3.8}$$

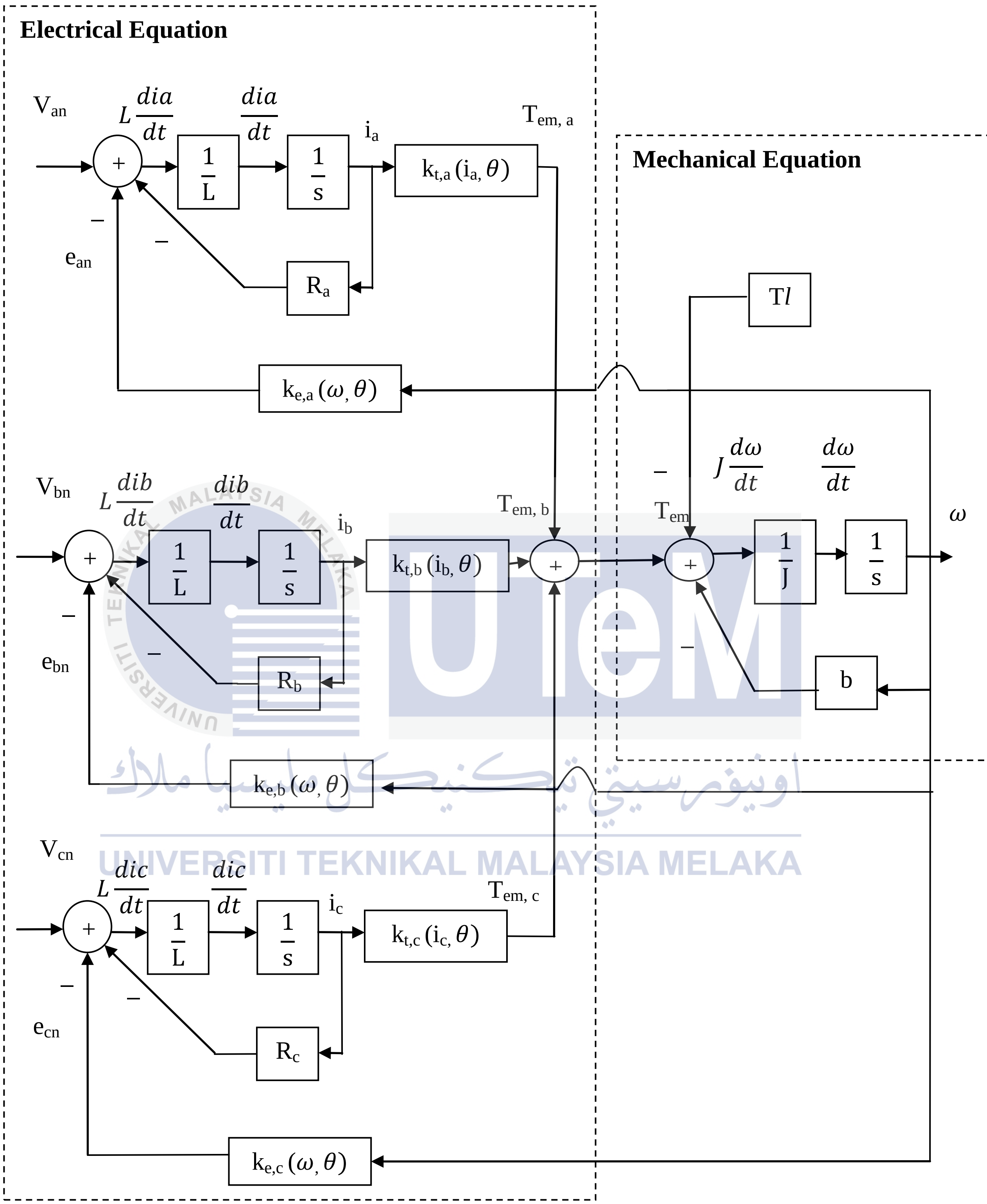

Figure 3.13 : BLDC Machine Model Block Diagram

3.4 Principle of DTC of BLDC

In the construction of DTC in BLDC, six non-zero voltage space vectors are defined [6] as shown in Figure 3.14. In addition, only two phases are conducting in the 120º conduction mode except during the commutation periods when all three phases conduct. In BLDC drive, six digits are necessary to represent the states of the inverter switches, one digit for each switch since the upper and lower switches in the same phase leg may both simultaneously off. The voltage space vectors V_1, V_2, V_3, V_4, V_5, V_6 are represented as switching signals (100 001), (001 001), (011 000), (010 010), (000 110), and (100 100). These values express the upper and lower switching signal for phases A, B, and C respectively [12]. The zero- voltage space vector is defined as (000 000). This can be seen in Figure 3.15.

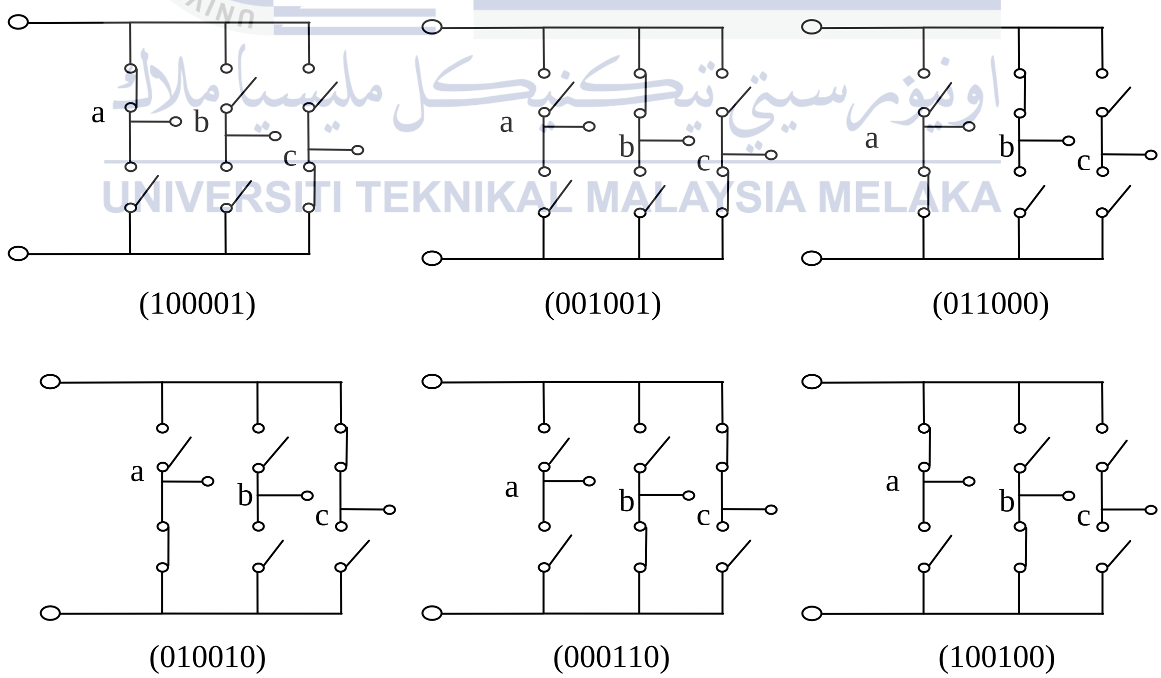

Figure 3.14 : Represent The States of The Inverter Switches for BLDC

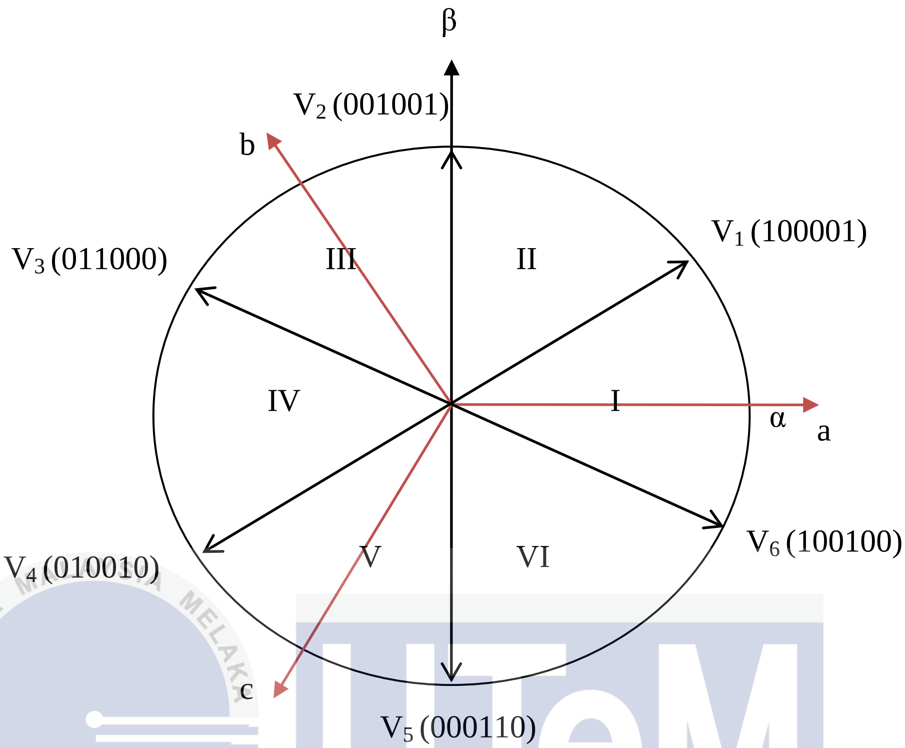

Figure 3.15 : The Voltage Space Vectors and Sectors for BLDC Motor in the α-β Reference Frame

Recently, application of Direct Torque Control (DTC) is extended to BLDC motor drives to minimize the switching frequency. It is claimed that under constant torque region of two-phase conduction mode, the stator flux linkage amplitude and the electromagnetic torque of the DTC of BLDC can be controlled simultaneously [23]. By eliminating the flux control in the constant torque region and deliberately keeping the stator flux linkage amplitude almost constant, it is shown that in two-phase conduction DTC of BLDC motor drive only torque is controlled. Since the flux control is removed and it is simplified to just a torque controlled drive, fewer algorithms are necessary for the proposed control scheme.

In the control scheme of two-conduction mode of DTC of BLDC, there is only two-phase conduct at any instant of time using six-switch inverter. The desired current waveform is obtained by selecting the appropriate inverter voltage space vectors of the two-phase conduction mode from a simple look-up table and hence, faster torque response is achieved.

In the constant torque region, correct estimation of the electromagnetic torque is the most important things in DTC of BLDC motor drive. Thus, it is preferred to obtain electromagnetic torque equation in stationary reference frame instead of synchronous frame for DTC of BLDC motor drive operation. The final electromagnetic equation which is given in the stationary reference frame is as below [23]:

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[\frac{e_\alpha}{\omega_e} i_{s\alpha} + \frac{e\beta}{\omega_e} i_{s\beta}\right] = \frac{3}{2}\frac{P}{2}\left[k_\alpha(\theta_e) i_{s\alpha} + k_\beta(\theta_e) i_{s\beta}\right] \tag{3.9}$$

where ωe is the electrical rotor speed, and $k\alpha(\theta e)$, $k\beta(\theta e)$, $e\alpha$, $e\beta$ are the stationary reference frame ($\alpha\beta$–axes) back-EMF constants according to electrical rotor position, motor back-EMFs, respectively. There will be no problem estimating the torque at zero and near zero speeds since the right hand side of the Equation (3.9) does not involve the rotor speed in the denominator. Therefore, it is used in the DTC of BLDC two-phase conduction mode control system instead of the one on the left hand side.

Conventional two-phase conduction quasi-square wave current control causes the locus of the stator flux linkage to be unintentionally kept in hexagonal shape if the unexcited open phase back-emf effect and the free-wheeling diodes are neglected, as shown in Figure 3.16 with dashed lines. If the free-wheeling diodes effect which is caused by commutation is ignored, more circular flux trajectory can be obtained [24].

From hysteresis controllers, by comparing the estimated electromagnetic torque and stator flux linkage with their demanded values the stator flux linkage and torque commands are obtained. Based on the stator-flux-linkage, torque status and the sector in which the stator flux linkage is located at any of time, the switching pattern of the inverter can be determined as in Figure 3.16. In DTC of BLDC with two-phase conduction mode, the flux error φ in the voltage vector look-up table is always selected as zero and only the torque error τ is used based on the error level of the actual torque from the reference torque. Within the hysteresis bandwidth, if the reference torque is bigger than the actual torque, the torque error τ is defined as '1' otherwise it is '-1' as shown in Table 3-7.

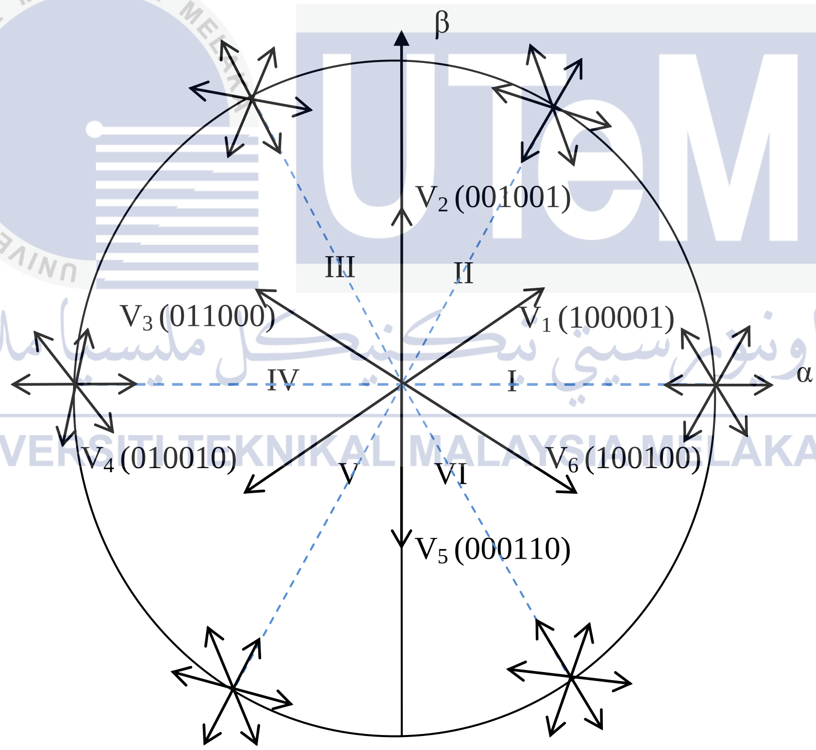

Figure 3.16 : Representation of two-phase Voltage Space Vectors

Table 3-7: Two-Phase Voltage Vector Selection for BLDC Motor

Stator flux error status, Ψ_s^+	**Torque error status, T_{stat}**	**Sector I**	**Sector II**	**Sector III**	**Sector IV**	**Sector V**	**Sector VI**
1	*1*	V_1 *(100001)*	V_2 *(001001)*	V_3 *(011000)*	V_4 *(010010)*	V_5 *(000110)*	V_6 *(100100)*
	-1	V_6 *(100100)*	V_1 *(100001)*	V_2 *(001001)*	V_3 *(011000)*	V_4 *(010010)*	V_5 *(000110)*
0	**1**	$\mathbf{V_2}$ **(001001)**	$\mathbf{V_3}$ **(011000)**	$\mathbf{V_4}$ **(010010)**	$\mathbf{V_5}$ **(000110)**	$\mathbf{V_6}$ **(100100)**	$\mathbf{V_1}$ **(100001)**
	-1	$\mathbf{V_5}$ **(000110)**	$\mathbf{V_6}$ **(100100)**	$\mathbf{V_1}$ **(100001)**	$\mathbf{V_2}$ **(001001)**	$\mathbf{V_3}$ **(011000)**	$\mathbf{V_4}$ **(010010)**
-1	*1*	V_3 *(011000)*	V_4 *(010010)*	V_5 *(000110)*	V_6 *(100100)*	V_1 *(100001)*	V_2 *(001001)*
	-1	V_4 *(010010)*	V_5 *(000110)*	V_6 *(100100)*	V_1 *(100001)*	V_2 *(001001)*	V_3 *(011000)*

Note : The italic area is not used in this two-phase conduction scheme DTC of BLDC motor drive

3.4.1 Control of Electromagnetic Torque by Selecting Proper Voltage Space Vector

A relationship is established between the torque, the flux and optimal switching inverter in order to achieve fast torque response. A change in the torque can be achieved by increasing the rotational speed of the stator flux linkage as fast as possible and keeping the amplitude of the stator flux linkage constant. By choosing the proper voltage vectors while keeping the flux amplitude almost constant, the rotational speed of the stator flux linkage can be controlled, meaning that the flux control is eliminated.

When a primary windings, which are assumed to be fed by an inverter using 2-phase conduction mode, as shown as Figure 3.17, the primary voltage V_{an}, V_{bn}, and V_{cn} are determined by the status of the six switches which are SW1, SW2, SW3,SW4, SW5 and SW6. For example, if SW1 is one (turned on) and SW2 is zero (turned off) then $V_{an} = V_{dc}/2$ and similarly for V_{bn} and V_{cn}. Since the upper and lower switches in a phase leg may both simultaneously off, six digits are required for the inverter operation, one digit for each switch. Thus,there is a total of six non-zero voltage vectors and a zero voltage vector for two-phase conduction mode as in Figure 3.17 [11].

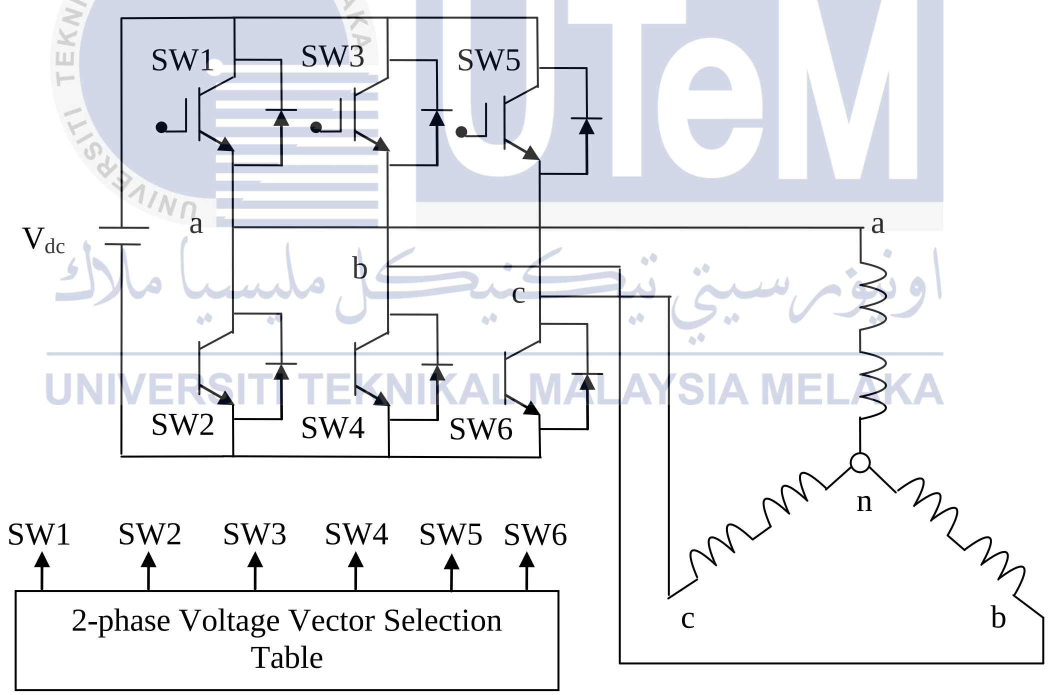

Figure 3.17: Representation of Two-phase Switching States of the Inverter Voltage Space Vector for a BLDC motor

3.4.2 Structure of DTC of BLDC

Figure 3.18 shows the complete DTC structure of BLDC motor. It consist of torque comparator, look-up table that shows the selection of voltage vector for every sector, inverter that connected to BLDC motor, three hall effect sensors mounted at the motor namely Ha, Hb, and Hc to detect the position of rotor and torque estimator as described in previous sections.

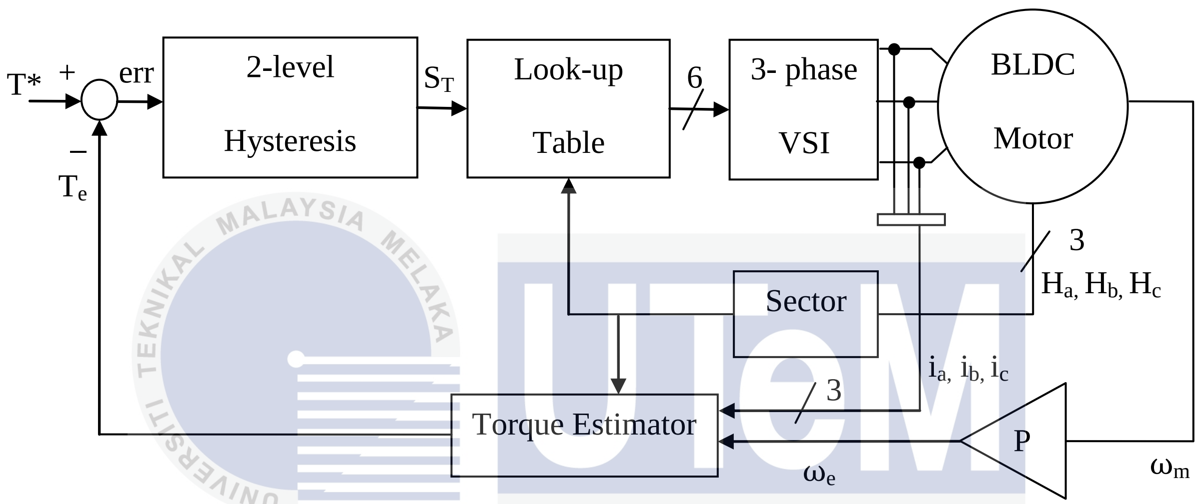

Figure 3.18: Structure of DTC

3.4.2.1 Simulation Model of DTC and THC of BLDC Motor

The overall block diagram of the closed-loop DTC and THC scheme of a BLDC motor drive in the constant torque region is represented in Figure 3.19. As for THC, the modeling of block diagram is not included in the scope of this research. In the case of modeling DTC of BLDC, it only requires torque control loop. Torque error that is obtained from the subtraction of torque reference and actual torque is the input to the two-level torque hysteresis comparator. This error will be limited within its hysteresis band. An appropriate voltage vector is selected to reduce or increase the torque error. The selection of sector and suitable voltage vectors or switching states is obtained from the look-up table. The sector will be generated from the hall-effect signal which are mounted at the BLDC motor and are define as H_a, H_b, H_c. In addition, the output current from three phase voltage source inverter (i_a, i_b, i_c) together with the electrical speed from the BLDC motor will estimate the motor's torque using torque estimator.

As for the Hall sensor, the commutation is simply achieved by driving current into two-phases while leaving the third phase open. The states of the Hall sensor decide which pair of phases will be used to drive current into. By using two switching power devices on each motor phase, the rotor position can be determined. Table 3-8 is the results from the commutation process in BLDC that involves the Hall Effect sensor. Every sector has its own hall-effect signal due to the position of rotor. For example, when Ha is energized, the digitized signal considered as 1. Likewise, when Ha is not energized, it is considered as 0.

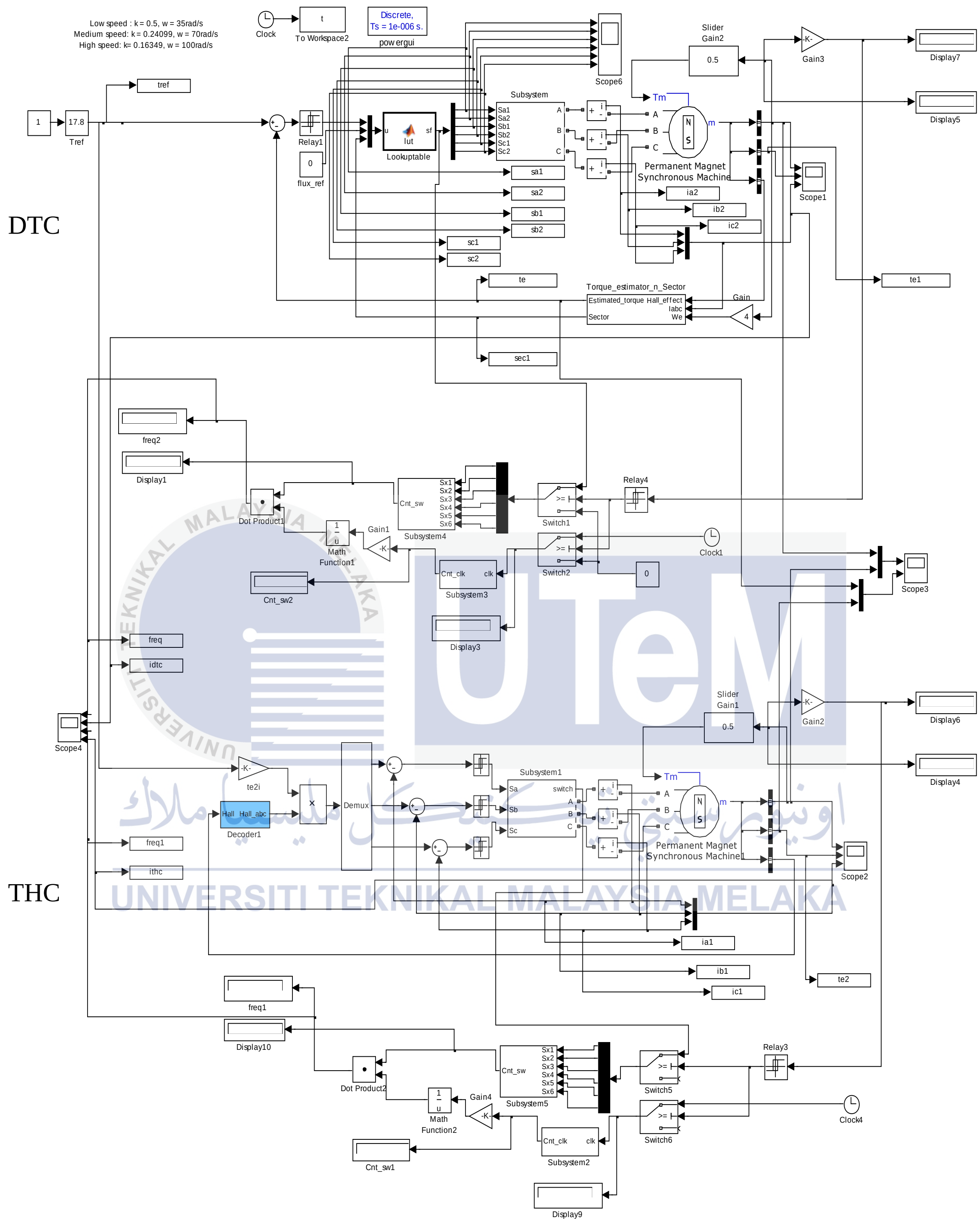

Figure 3.19: Simulation Model of DTC and THC of BLDC Motor Drive

Table 3-8 : Appropriate Sector Based on Hall Effect

Hall-effect Signal			Sector
H_a	H_b	H_c	
1	1	0	1
0	1	0	2
0	1	1	3
0	0	1	4
1	0	1	5
1	0	0	6

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Simulation Results and Discussion

This project is expected to achieve the desired objective which is to model and simulate the Direct Torque Control (DTC) of Brushless DC Motor (BLDC) by using Matlab or Simulink. Other than that, the results from this simulation need to be analyze and compare in terms of the switching frequency and torque/current control performances due to variations of speed and hysteresis bandwidth produced in Direct Torque Control (DTC) and Torque Hysteresis Control (THC) of Brushless DC Motor (BLDC) drive. Below are the parameters used for both DTC and THC.

Table 4-1: Parameters for DTC and THC

DC input Voltage, V_{dc} (V)	320
Sampling Time, T_s (μs)	$1e^{-6}$
Torque Limit, T_{Lim} (Nm)	17.8
Flux reference, F_{ref} (Wb)	0
No of pole, p	8
Torque load, T_L or k (N_m)	0.5, 0.24099 and 0.16349
Stator phase resistance, Rs (ohm)	0.2
Stator phase inductance, Ls (H)	$8.5e^{-3}$

Equation 4.1 shows equation expresses in general form about the conversion of torque to current. Torque limit (T_{Lim}) given as 17.8 Nm in DTC model (Equation 4.2) is converted to current in order to implement it in THC. It is used to calculate the bandwidth of the hysteresis comparator for both DTC and THC.

$$\text{Ipeak} = \frac{\text{TLim}}{2\text{x}4\text{x}0.175} \tag{4.1}$$

$$\text{Ipeak} = \frac{17.8}{2\text{x}4\text{x}0.175} = 12.714\text{A} \tag{4.2}$$

Where 2x4 is the number of pole pairs and 0.175 is the value of flux linkage.

i. Low speed: k = 0.5, w = 337 rpm

Table 4-2 shows the value of switching frequencies for DTC and THC in low speed due to variations of current and torque bandwidth (HB_I and HB_T). From here, it can be seen that the smaller the bandwidth, the higher the switching frequency for both DTC and THC. This table indicates that DTC have higher switching frequencies for every percentage of current than THC.

Table 4-2: Frequency of DTC and THC (Low Speed) with Different Hysteresis Bandwidth

% of Ipeak	**10% Ipeak**	**15% Ipeak**	**20% Ipeak**	**25% Ipeak**
HB_I	1.2714/2	1.9071/2	2.5428/2	3.1785/2
HB_T	0.88998	1.33497	1.77996	2.22495
DTC (kHZ)	53.48	36.2	27.47	22.03
THC (kHZ)	45.75	28.14	17.63	15.91

ii. Medium speed: k = 0.24099, w = 672 rpm

Table 4-3 shows the value of switching frequencies for DTC and THC in medium speed due to variations of current and torque bandwidth (HB_I and HB_T). From here, it can be seen that the smaller the bandwidth, the higher the switching frequency for both DTC and THC. This table indicates that DTC have higher switching frequencies for every percentage of current than THC.

Table 4-3 : Frequency of DTC and THC (Medium Speed) with Different Hysteresis Bandwidth

% of Ipeak	10% Ipeak	15% Ipeak	20% Ipeak	25% Ipeak
HB_I	1.2714/2	1.9071/2	2.5428/2	3.1785/2
HB_T	0.88998	1.33497	1.77996	2.22495
DTC (kHZ)	44.75	30.45	23.19	18.73
THC (kHZ)	24.12	16.28	12.98	11.44

iii. High speed: k = 0.16349, w = 953 rpm

Table 4-4 shows the value of switching frequencies for DTC and THC in high speed due to variations of current and torque bandwidth (HB_I and HB_T). From here, it can be seen that the smaller the bandwidth, the higher the switching frequency for both DTC and THC. This table indicates that DTC have higher switching frequencies for every percentage of current than THC.

Table 4-4: Frequency of DTC and THC (High Speed) with Different Hysteresis Bandwidth

% of Ipeak	10% Ipeak	15% Ipeak	20% Ipeak	25% Ipeak
HB_I	1.2714/2	1.9071/2	2.5428/2	3.1785/2
HB_T	0.88998	1.33497	1.77996	2.22495
DTC (kHZ)	33.43	22.96	17.46	14.13
THC (kHZ)	24.01	16.21	12.53	10.75

This thesis only shows the waveform of torque and current resulted in DTC and THC from 20% of Ipeak where HB_I is 2.5428/2 and HB_T is equal to 1.77996 in every speed operating ranges. Figure 4.1 shows the comparison of torque and current waveform between DTC and THC in low speed (337 rpm) condition. From here, it is clearly shown that torque regulation performance of DTC is better than THC due to the selection of voltage vector. As for the switching frequency, DTC produce high switching frequency than in THC.

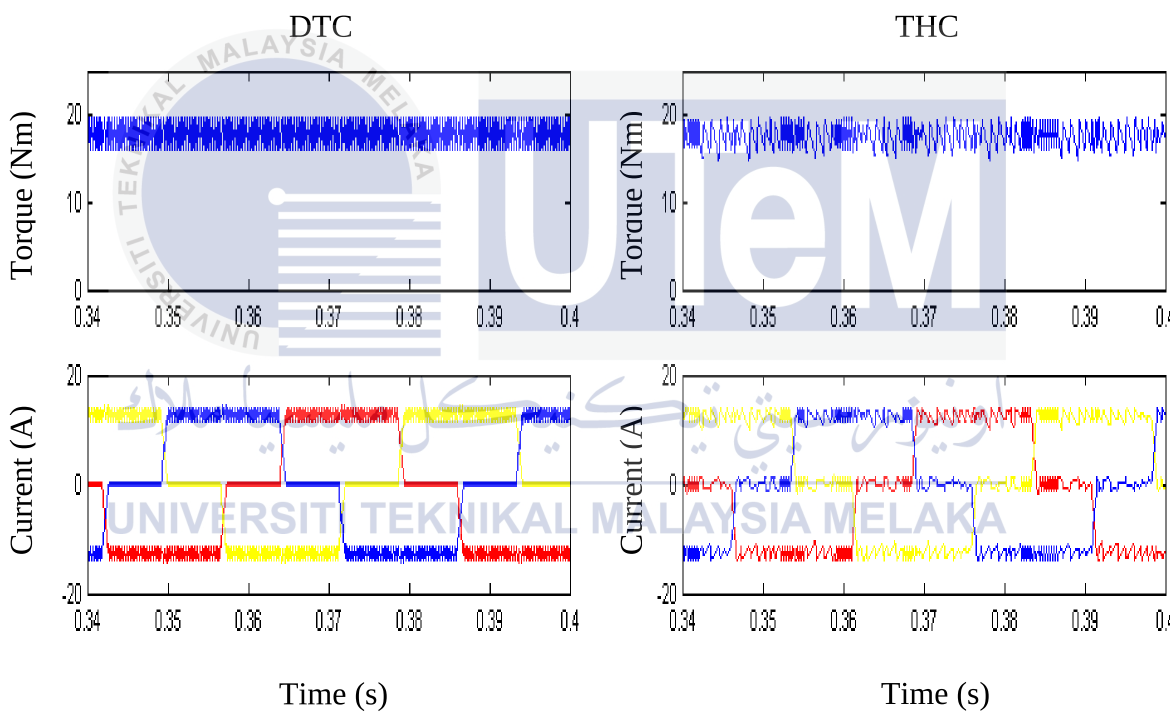

Figure 4.1: 20% of Ipeak (Low Speed) for DTC and THC

Figure 4.2 shows the comparison of torque and current waveform between DTC and THC in medium speed (672 rpm) condition. From here, it is clearly shown that torque regulation performance of DTC is better than THC due to the selection of voltage vector. As for the switching frequency, DTC produce high switching frequency than in THC.

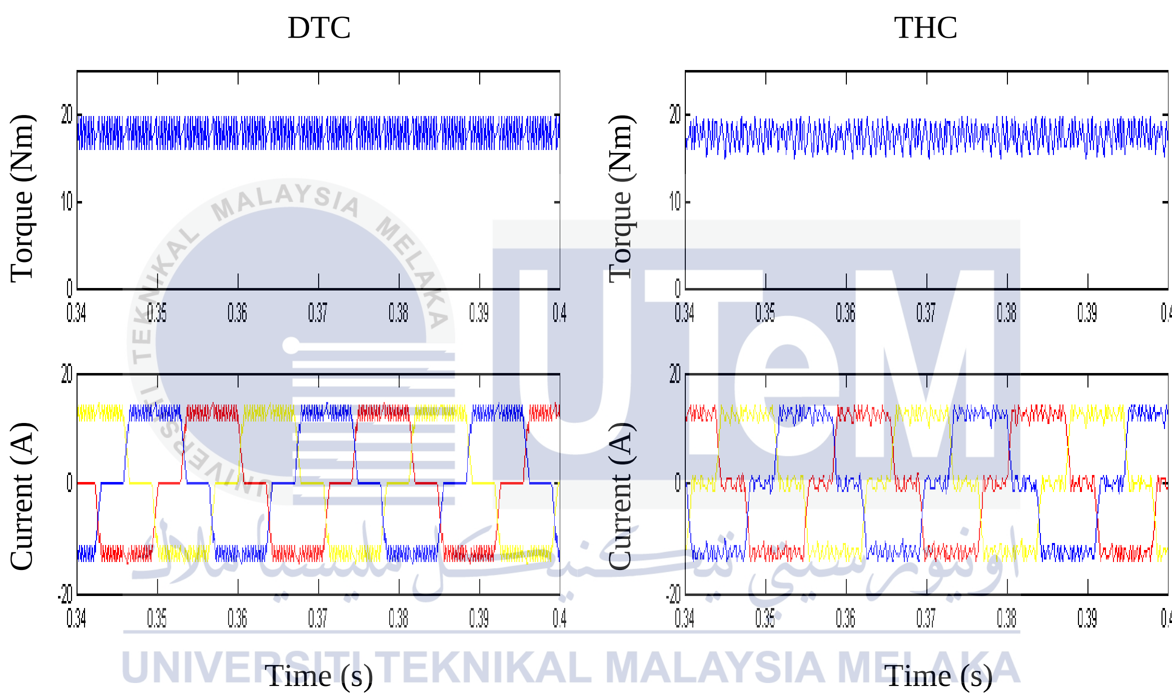

Figure 4.2: 20% of Ipeak (Medium Speed) for DTC and THC

Figure 4.3 shows the comparison of torque and current waveform between DTC and THC in high speed (953 rpm) condition. From here, it is clearly shown that torque regulation performance of DTC is better than THC due to the selection of voltage vector. As for the switching frequency, DTC produce high switching frequency than in THC.

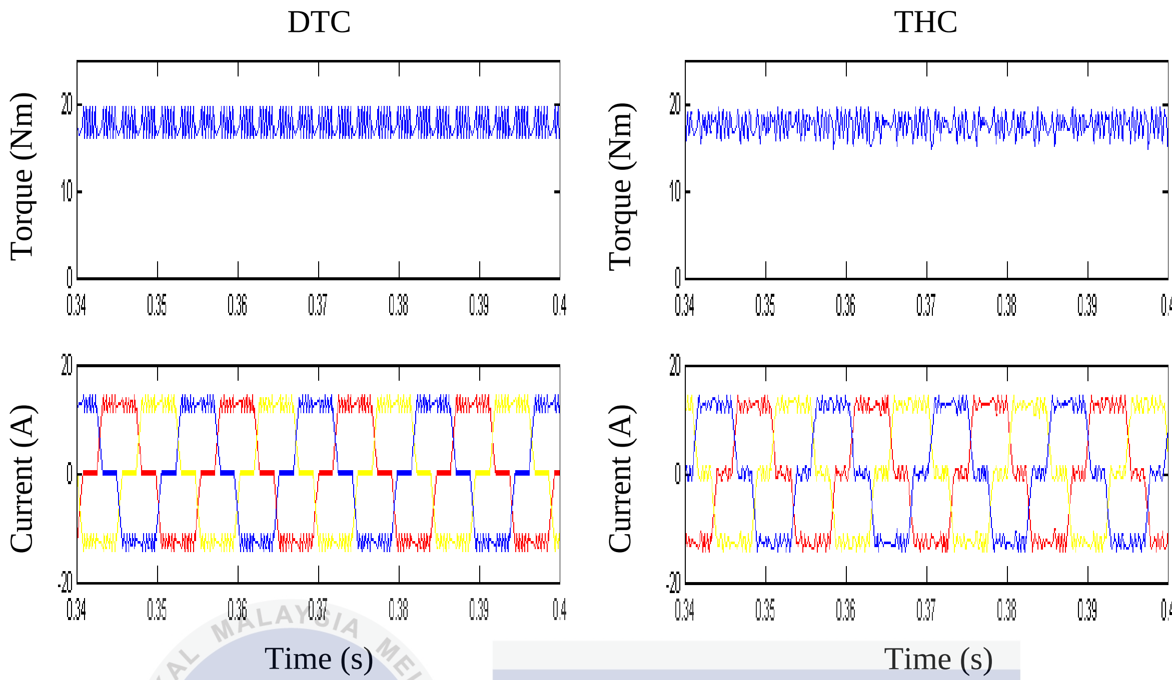

Figure 4.3: 20% of Ipeak (High Speed) for DTC and THC

The graph in Figure 4.4 clearly shows DTC have high switching frequency compared to THC in low speed (337 rpm) condition. Reduced bandwidth resulted in high switching frequency.

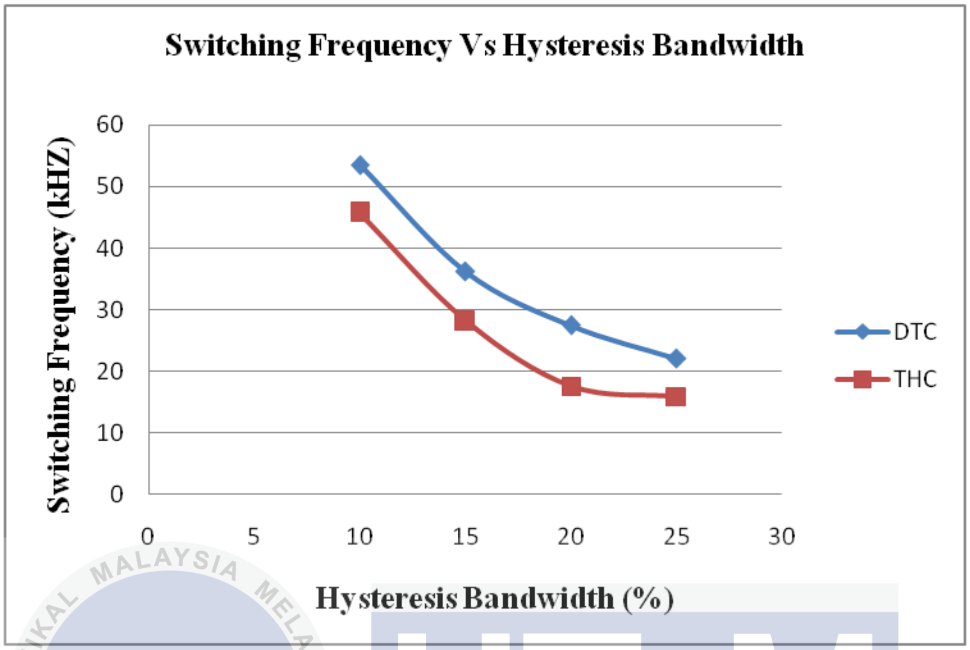

Figure 4.4: Switching Frequency vs Hysteresis Bandwidth (Low Speed)

The graph in Figure 4.5 clearly shows DTC have high switching frequency compared to THC in medium speed (672 rpm) condition. Reduced bandwidth resulted in high switching frequency.

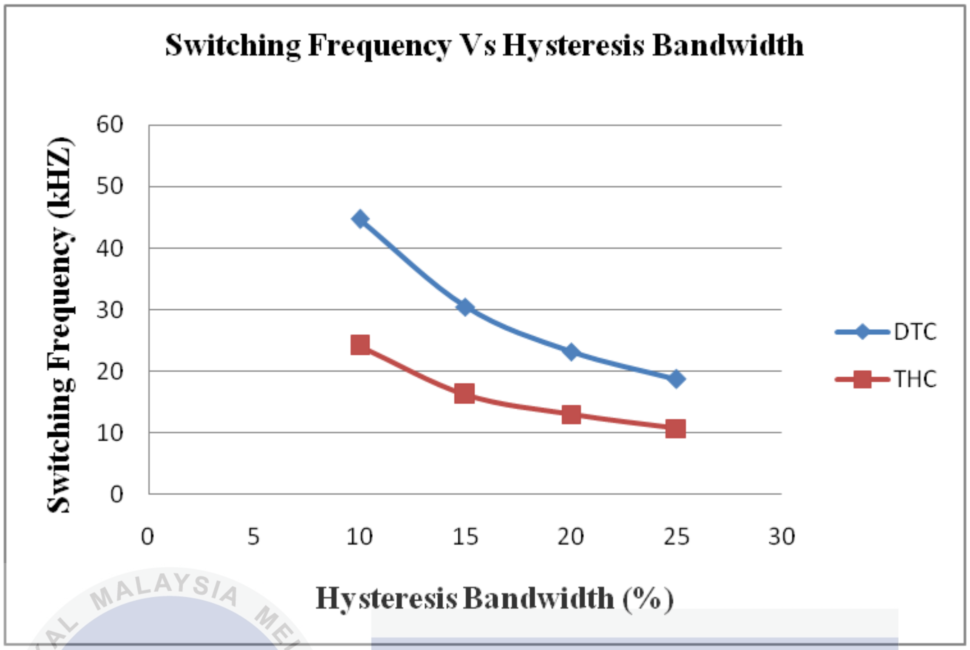

Figure 4.5: Switching Frequency vs Hysteresis Bandwidth (Medium Speed)

The graph in Figure 4.6 clearly shows DTC have high switching frequency compared to THC in high speed (953 rpm) condition. Reduced bandwidth resulted in high switching frequency.

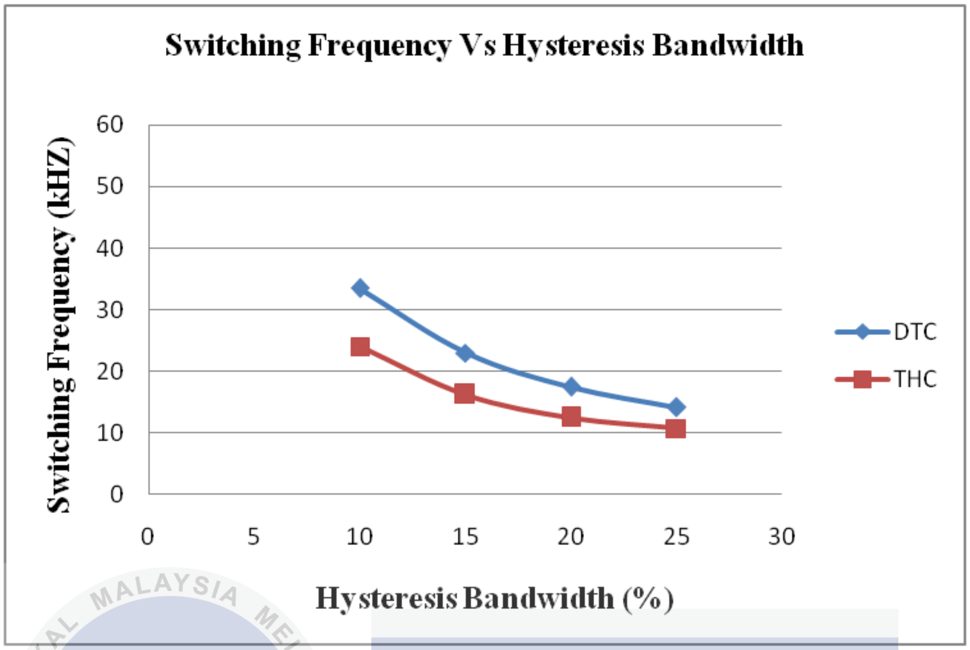

Figure 4.6: Switching Frequency vs Hysteresis Bandwidth (High Speed)

4.2 Overall Discussion

This project is aimed to analyze and compare the switching frequency and torque/current control performances produced in Direct Torque Control (DTC) and Torque Hysteresis Control (THC) of Brushless DC Motor (BLDC) drive. It is known that, low switching frequency results in high efficiency of the system. It is expected that, DTC produces low switching frequency than THC because DTC operates in two-phase conduction mode, as only two-phase produces switching at any instant of time. As for THC, the switching results in three-phase. From the graph obtained in Figures 4.1,4.2 and 4.3 it can be observed that the switching of phase current in THC still occurs whenever the current need to be regulated at zero (0) Ampere. However, the switching frequency is small compared to DTC due to the possibility of low switching frequency at every phase of i_a , i_b and i_c. As for DTC, even though only two-phase operates in any instant of time, the switching frequency in two-phase, i_a and i_b is higher than THC thus, affecting overall switching frequency of DTC of BLDC.

Major drawback of hysteresis is having an unpredictable non linear frequency. Switching frequency varies based on the operating condition such as load, torque, dc voltage, speed, variation of parameters, temperature and etc. In this project, the comparisons of switching frequency between DTC and THC are tested in several speed conditions that are low speed (337 rpm), medium speed (672 rpm) and high speed (953 rpm). It is proven from Table 4-2, at low speed (extreme condition), switching frequencies produce in both DTC and THC are high compared to other speed condition (Table 4-2 and 4-3). For worst case such as very low speed or extreme high torque load (T_L), switching frequency can extend beyond the limitation of switching device (IGBT). If the switching frequency exceeds the limitation, it will drop the IGBT performance in terms of drop voltage, increase losses and its reliability. In long terms, the IGBT will damage.

Significant study on performance of switching frequency or efficiency is related to the minimization of torque or current ripple which is necessary to achieve excellent performance. This can be obtained by reducing the hysteresis bandwidth such that the torque or current ripple can be restricted within reduced bandwidth. However, reduce hysteresis bandwidth produce high frequencies since the regulation within bandwidth is more often. It shorten the time to travel (torque variation in bandwidth) from one band to another band. In this project, the bandwidth is reduced by percentage of peak current (Ipeak) obtain from Equation (4.1). However, small bandwidth results in high switching frequency. DTC is mainly affected by the switching in torque hysteresis controller (two conduction or phase switching) while for THC, it is produced by switching in current hysteresis controllers (involve three conduction or phase switching). Both torque and current bandwidth of DTC and THC have been reduced to a certain values. As the bandwidth is reduced, the switching frequency for DTC and THC will increase but, it is expected to produce low switching frequencies in DTC compared to THC. However, the results are not achievable. It has been proved through result in Figure 4.4, 4.5 and 4.6 that DTC produce high switching frequency than THC in every speed operating conditions. Even though DTC operates at two-phase conduction mode, THC still produces lower switching frequency than DTC.

Other aspect to look at is the torque regulation performance. Poor torque regulation performance in THC have been improved by DTC. Examples from Figure 4.1, 4.2 and 4.3, (20% of Ipeak) proved that current or torque ripple of THC is not restricted within predefined hysteresis bandwidth. As for DTC, it has better torque regulation performance than THC. Thus, from the explanation above, it can be concluded that both DTC and THC have their own advantages and disadvantages. DTC have better torque regulation performance but high switching frequency while THC has poor regulation performance with low switching frequency.

CHAPTER 5

CONCLUSION AND RECCOMENDATION

5.1 Conclusion

It is concluded that the desired objectives are successfully achieved in terms of modeling DTC of BLDC and there is some comparisons have been made between DTC and THC. However, from the simulation results by Matlab, the expected results are not achievable. The purpose of DTC and THC is the same, which is minimizing the torque ripple. In order to reduce torque ripple the hysteresis bandwidth should be reduced. Thus, increase the switching frequencies for both DTC and THC because the regulation within bandwidth is more often. Supposedly, expected results in DTC are having low switching frequencies than THC in order to show that DTC is more efficient and have better performance than THC. However, simulation results show that DTC produce higher switching frequency than THC which mean that the expected result is not obtainable. In addition, poor torque regulation performance in THC have been improved in DTC. From these results it is concluded that both DTC and THC has its own advantages and disadvantages. It is proved DTC has better torque regulation performance and high switching frequency while THC has poor torque regulation performance but low switching frequency.

5.2 Recommendation

Simulation results through Matlab proved that DTC of BLDC have better torque regulation but have higher switching frequency than THC. In order to operate at high efficiency, it is suggested to limit the switching frequency at constant regulation [25]. In this research, hysteresis comparator is used and resulting in non-linear torque regulation. Figure 5.1(a) and (b) Shows the switching frequency resulted in using the hysteresis comparator while Figure 5.2(a) and (b) shows the suggested or recommended method. The switching frequency is determined by triangular/carrier signal and it is constant for every operating condition. Thus, the switching frequency does not exceed beyond limitation of IGBT and have better torque regulation performance.

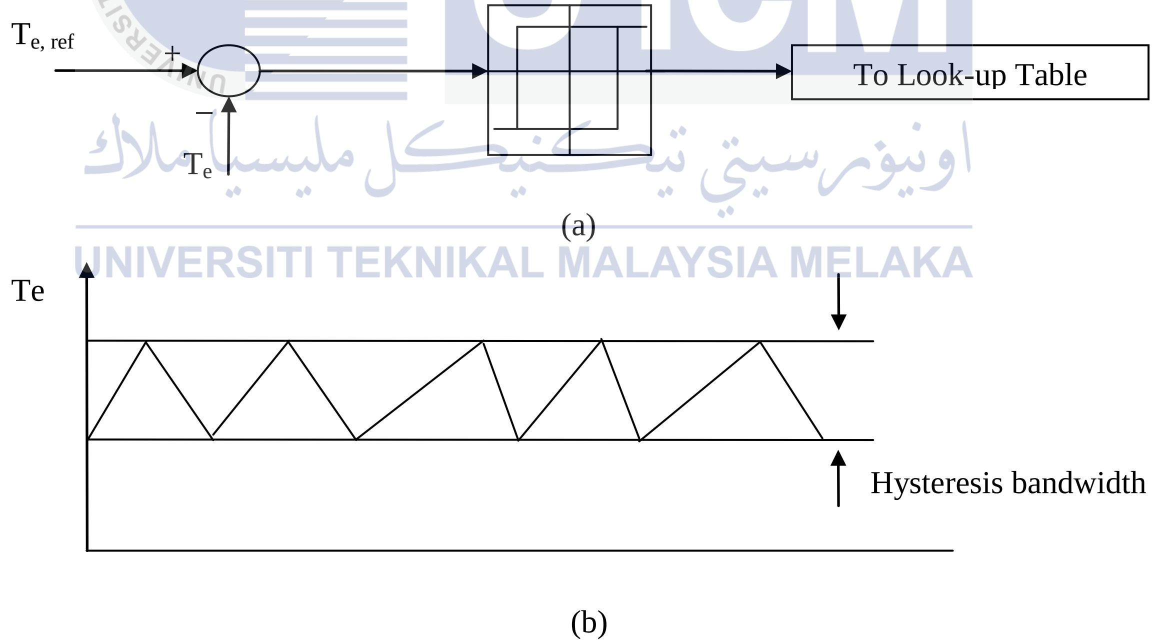

Figure 5.1 :(a) Control Torque Using Hysteresis Comparator (b) Non-linear Switching Frequency Resulted from Hysteresis Comparator

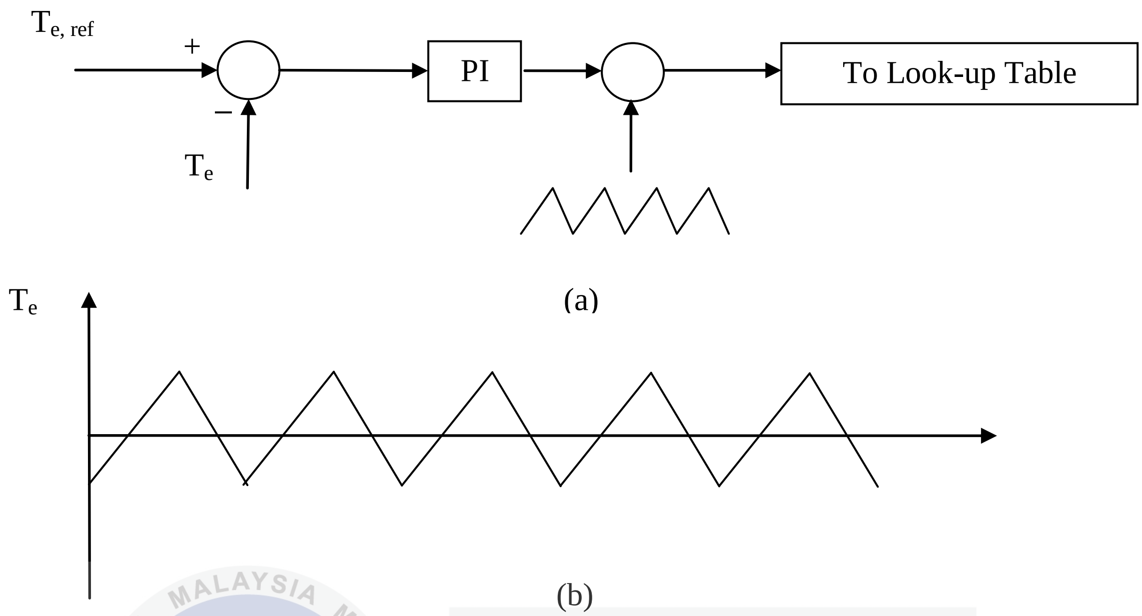

Figure 5.2 :(a) Control Torque Using Carrier-Base (b) Constant Switching Frequency Resulted from Carrier Signal

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APPENDICES

1. Programming of Voltage Vector Selection Based on Table 3-7.

The objective of this program is to select the switching states of voltage vector and helps in the development of the look-up table for DTC of BLDC. Flux error status is considered as 1, 0 or -1 while torque error status is considered as 1 and -1.

```
%inputs: torque u(1), flux u(2)  and angle u(3)
%Salih Baris

function sf = lut(u)
s1=0;
s2=0;
s3=0;
s4=0;
s5=0;
s6=0;
x=u(1);
y=u(2);
ang=u(3);

%torque =1 sector =1 flux=1,0,-1
if   (x== 1 &&  ang == 1 && y == 1)
     s1 = 1; s2 = 0; s3 = 0; s4 =0; s5 =0; s6 =1; %V1
end
if (x == 1 && ang == 1 && y == 0)
     s1 = 0; s2 = 0; s3 = 1; s4 =0; s5 =0; s6 =1; %V2
end
if (x == 1 && ang == 1 && y == -1)
     s1 = 0; s2 = 1; s3 = 1; s4 =0; s5 =0; s6 =0; %V3
end

%torque =1 sector =2 flux=1,0,-1
if (x == 1 && ang == 2 && y == 1)
      s1 = 0; s2 = 0; s3 = 1; s4 =0; s5 =0; s6 =1;  %V2
end
if (x == 1 && ang == 2 && y == 0)
      s1 = 0; s2 = 1; s3 = 1; s4 =0; s5 =0; s6 =0;  %V3
end
if (x == 1 && ang == 2 && y == -1)
      s1 = 0; s2 = 1; s3 = 0; s4 =0; s5 =1; s6 =0;  %V4
end

%torque =1 sector =3 flux=1,0,-1
if(x == 1 && ang == 3 && y == 1)
```

```
     s1 = 0; s2 = 1; s3 = 1; s4 =0; s5 =0; s6 =0; %V3
end
if(x == 1 && ang == 3 && y == 0)
     s1 = 0; s2 = 1; s3 = 0; s4 =0; s5 =1; s6 =0; %V4
end
if(x == 1 && ang == 3 && y == -1)
     s1 = 0; s2 = 0; s3 = 0; s4 =1; s5 =1; s6 =0; %V5
end

%torque =1 sector =4 flux=1,0,-1
if(x == 1 && ang == 4 && y == 1)
    s1 = 0; s2 = 1; s3 = 0; s4 =0; s5 =1; s6 =0;  %V4
end
if(x == 1 && ang == 4 && y == 0)
    s1 = 0; s2 = 0; s3 = 0; s4 =1; s5 =1; s6 =0; %V5
end
if(x == 1 && ang == 4 && y == -1)
    s1 = 1; s2 = 0; s3 = 0; s4 =1; s5 =0; s6 =0; %V6
end

%torque =1 sector =5 flux=1,0,-1
if(x == 1 && ang == 5 && y == 1)
   s1 = 0; s2 = 0; s3 = 0; s4 =1; s5 =1; s6 =0; %V5
end
if(x == 1 && ang == 5 && y == 0)
   s1 = 1; s2 = 0; s3 = 0; s4 =1; s5 =0; s6 =0; %V6
end
if(x == 1 && ang == 5 && y == -1)
   s1 = 1; s2 = 0; s3 = 0; s4 =0; s5 =0; s6 =1; %V1
end

%torque =1 sector =6 flux=1,0,-1
if(x == 1 && ang == 6 && y == 1)
   s1 = 1; s2 = 0; s3 = 0; s4 =1; s5 =0; s6 =0; %V6
end
if(x == 1 && ang == 6 && y == 0)
   s1 = 1; s2 = 0; s3 = 0; s4 =0; s5 =0; s6 =1; %V1
end
if(x == 1 && ang == 6 && y == -1)
   s1 = 0; s2 = 0; s3 = 1; s4 =0; s5 =0; s6 =1; %V2
end

%torque =-1 sector =1 flux=1,0,-1
if   (x== -1 &&  ang == 1 && y == 1)
     s1 = 1; s2 = 0; s3 = 0; s4 =1; s5 =0; s6 =0; %V6
end
if (x == -1 && ang == 1 && y == 0)
     s1 = 0; s2 = 0; s3 = 0; s4 =1; s5 =1; s6 =0; %V5
end
if (x == -1 && ang == 1 && y == -1)
     s1 = 0; s2 = 1; s3 = 0; s4 =0; s5 =1; s6 =0; %V4
end

%torque =-1 sector =2 flux=1,0,-1
if (x == -1 && ang == 2 && y == 1)
      s1 = 1; s2 = 0; s3 = 0; s4 =0; s5 =0; s6 =1;  %V1
```

```
end
if (x == -1 && ang == 2 && y == 0)
      s1 = 1; s2 = 0; s3 = 0; s4 =1; s5 =0; s6 =0;  %V6
end
if (x == -1 && ang == 2 && y == -1)
      s1 = 0; s2 = 0; s3 = 0; s4 =1; s5 =1; s6 =0;   %V5
end

%torque =-1 sector =3 flux=1,0,-1
if(x == -1 && ang == 3 && y == 1)
     s1 = 0; s2 = 0; s3 = 1; s4 =0; s5 =0; s6 =1; %V2
end
if(x == -1 && ang == 3 && y == 0)
     s1 = 1; s2 = 0; s3 = 0; s4 =0; s5 =0; s6 =1; %V1
end
if(x == -1 && ang == 3 && y == -1)
     s1 = 1; s2 = 0; s3 = 0; s4 =1; s5 =0; s6 =0; %V6
end

%torque =-1 sector =4 flux=1,0,-1
if(x == -1 && ang == 4 && y == 1)
    s1 = 0; s2 = 1; s3 = 1; s4 =0; s5 =0; s6 =0;  %V3
end
if(x == -1 && ang == 4 && y == 0)
    s1 = 0; s2 = 0; s3 = 1; s4 =0; s5 =0; s6 =1; %V2
end
if(x == -1 && ang == 4 && y == -1)
    s1 = 1; s2 = 0; s3 = 0; s4 =0; s5 =0; s6 =1; %V1
end

%torque =-1 sector =5 flux=1,0,-1
if(x == -1 && ang == 5 && y == 1)
   s1 = 0; s2 = 1; s3 = 0; s4 =0; s5 =1; s6 =0; %V4
end
if(x == -1 && ang == 5 && y == 0)
   s1 = 0; s2 = 1; s3 = 1; s4 =0; s5 =0; s6 =0; %V3
end
if(x == -1 && ang == 5 && y == -1)
   s1 = 0; s2 = 0; s3 = 1; s4 =0; s5 =0; s6 =1; %V2
end

%torque =-1 sector =6 flux=1,0,-1
if(x == -1 && ang == 6 && y == 1)
   s1 = 0; s2 = 0; s3 = 0; s4 =1; s5 =1; s6 =0; %V5
end
if(x == -1 && ang == 6 && y == 0)
   s1 = 0; s2 = 1; s3 = 0; s4 =0; s5 =1; s6 =0; %V4
end
if(x == -1 && ang == 6 && y == -1)
   s1 = 0; s2 = 1; s3 = 1; s4 =0; s5 =0; s6 =0; %V3
end


sf=[s1; s2; s3; s4; s5; s6];
end
```

2. Hall Effect to Sector

The objective of this program is to select in which sector the position of rotor is located at. The position of rotor of the BLDC motor drive is identified with the help of Hall Effect Sensor.

```
%inputs: Ha u(1), Hb u(2) and Hc u(3)

function sf = lut(u)
Sector=0;
x=u(1);
y=u(2);
z=u(3);

if   (x== 1 &&  y == 1 && z == 0)
     Sector = 1;
end
if (x == 0 && y == 1 && z == 0)
     Sector = 2;
end
if (x == 0 && y == 1 && z == 1)
     Sector = 3;
end
if   (x== 0 &&  y == 0 && z == 1)
     Sector = 4;
end
if (x == 1 && y == 0 && z == 1)
     Sector = 5;
end
if (x == 1 && y == 0 && z == 0)
     Sector = 6;
end

sf=Sector;
end
```