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FINAL YEAR PROJECT REPORT II

SENSORLESS CONTROL OF PMSM DRIVES USING VOLTAGE MODEL BASED ON POWER REACTIVE EQUATION

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SENSORLESS CONTROL OF PMSM DRIVES USING VOLTAGE MODEL BASED ON POWER REACTIVE EQUATION

MUHAMMAD AMIRUL ASYRAF BIN MAHMUDDIN

A report submitted in partial fulfillment of the requirement for the degree of Electrical Engineering (Industrial Power)

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I declare that this report "*Sensorless control of PMSM drives using voltage model based on Power Reactive Equation*" 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 the candidature of any other degree.

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ABSTRACT

Permanent Magnet Synchronous Motor is versatile motor that have many advantages and it's generally used in many industrial applications for high performance as variable speed drives. Permanent Magnet Synchronous Motor typically used in variety of industrial application in order to replacing classic DC motor and induction motor. Plus, this motor brings a huge advantage such as high efficiency, high power density, lower field copper loss and more sturdy construction because of the DC field winding of rotor is swapped by permanent magnet. Mostly, PMSM comes with a mechanical sensor such as encoder, observer or Hall effect sensor that reduced its reliability, additional cost, increased complexity and weight of the drive system. This report proposed the development and model a sensorless control of PMSM drives using Matlab/Simulink. The modelling of sensorless control of PMSM drives using voltage model based on Model Reference Adaptive Control (MRAC) based on Power Reactive Equation in order to estimate the rotor position. The performance of this sensorless control will be analyzed and compared to standard PMSM Drives in term of speed behavior and load disturbance. The results show that the MRAC based on Power Reactive Equation have lack in satisfies the speed estimation and load disturbance compared to standard PMSM using sensor. However, this project has successfully created a sensorless control of PMSM that suitable for middle speed range.

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ABSTRAK

"Permanent Magnet Synchronous Motor" adalah motor serba boleh yang mempunyai banyak kelebihan dan ia biasanya digunakan dalam pelbagai aplikasi industri yang mempunyai kecekapan yang tinggi sebagai pemacu kelajuan boleh ubah. "Permanent Magnet Synchronous Motor" biasanya digunakan dalam pelbagai aplikasi industri untuk menggantikan klasik DC motor dan motor aruhan. Tambahan pula, motor ini membawa kelebihan yang besar seperti kecekapan tinggi, ketumpatan kuasa yang tinggi, lebih rendah kehilangan kuasa kuprum dan pembinaan yang lebih kukuh kerana medan penggulungan DC sudah ditukar kepada magnet kekal. Kebanyakannya, PMSM dilengkapi dengan sensor mekanikal seperti pengekod, pemerhati atau sensor "Hall effect" kesan yang mengurangkan kos, peningkatan kerumitan dan berat sistem pemacu. Laporan ini mencadanganganka pembuatan tanpa sensor untuk pemacu PMSM menggunakan Matlab / Simulink. Pemodelan kawalan tanpa sensor PMSM menggunakan "Model Reference Adaptive Control" (MRAC) berdasarkan persamaan "Power Reactive" untuk menganggarkan kedudukan motor. Prestasi kawalan tanpa sensor ini akan dianalisis dan dibandingkan dengan Pemacu PMSM standard dari segi tingkah laku kelajuan dan beban gangguan. Keputusan menunjukkan bahawa MRAC berdasarkan persamaan "Power Reactive" mempunyai kekurangan dalam memenuhi anggaran kelajuan dan beban gangguan berbanding PMSM standard menggunakan sensor. Walau bagaimanapun, projek ini telah berjaya mewujudkan kawalan tanpa sensor PMSM yang sesuai untuk kelajuan sederhana.

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NOMENCLATURE

Abbreviations

DTC - Direct Torque Control
EKF - Extended Kalman Filter
EMF - Electromotive force
EV - Electric Vehicle
FOC - Field Oriented Control
HF - High Frequency
INFORM - Indirect Flux Detection by On-Line Reactance Measurement
IPMSM - Internal Permanent Magnet Synchronous Motor
MRAS - Model Reference Adaptive System
MRAC - Model Reference Adaptive Control
SMO - Sliding Mode Observer
SNR - Signal to Noise Ratio
SVPWM - Space Vector Pulse Width Modulation
SPMSM - Surface Permanent Magnet Synchronous Motor
PMSM - Permanent Magnet Synchronous Motor

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Symbols

$\alpha\beta$	Stationary stator reference frame axes
β	viscous friction coefficient
ζ	damping ratio
ε	error
f	frequency
ud, uq	d-q axis stator voltage
id, iq	d-q axis current

Ld, Lq	d-q axis inductance
Rs	Stator resistance
Kp, Ki	Proportional and Integral controller
K_T	Torque constant
p	number of pair poles
Te	electrical motor torque
J	inertia of the rotor
ωm	reference rotor speed
Ψpm	permanent magnet flux
$\psi d, \psi q$	d-q axis stator flux
Vdc	DC link voltage
θ	angular position

Subscripts

a,b,c	Stator a,b,c phases

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CHAPTER 1

INTRODUCTION

1.1 Researched Background

Permanent Magnet Synchronous Motor (PMSM) is electronically commutated and this mechanism needs rotor position information. Nowadays, PMSM is commonly used in many industrial application as a high performance of variable speed drives. Plus, the PMSM is typically used in variety of industrial application in order to replacing classic dc and induction machine drives[1]. In permanent magnet synchronous motor, the dc field winding of the rotor is swapped by permanent magnet and this brings a huge advantage such as lower rotor inertia, lower copper loss, higher power density and more sturdy structure of the rotor[2].

Currently, AC motors are positively utilized as a part of numerous mechanical applications. Squirrel cage induction motor are quite popular used in industry because of it is basic structure, low creation cost and less maintenance. However, the induction motor has some disadvantages is maintaining it is working speed as the load torque is increase. Hence, the induction motors are not sufficient enough for application which require as exact control of speed and position like servo motors. Squirrel cage induction motors also have some disadvantages for example poor power factor and low efficiency as compared to synchronous motor[2].

On the contrary, synchronous motors is capable to accurately controlled by adjusting the frequency of the rotating magnetic field which is called as synchronous speed. But, the synchronous motor has some problem with noise due to the use of commutator and carbon brushes and also be affected with high production cost and maintenance cost [2]. These problem have led to the breakthrough of PMSM with permanent magnet excitation on the rotor. The advantages of PMSM are compactness, high efficiency, high power factor, rapid dynamic response, simple modeling and control, high torque to inertia ratio, rugged construction and minor maintenance[3],[4]. But, mostly the PMSM application always come with position sensor such as Hall Effect sensor or shaft encoder that has many disadvantages such as reduce a reliability, increase complexity, requires additional cost and weight, increase drive size and present more maintenance requirement [1]-[13]. For these reasons, researchers have been focusing on the elimination of position sensor at the motor shaft without reducing it dynamic performances of the drive and the development of position sensorless technique is becoming an important research area for nearly last two decades.

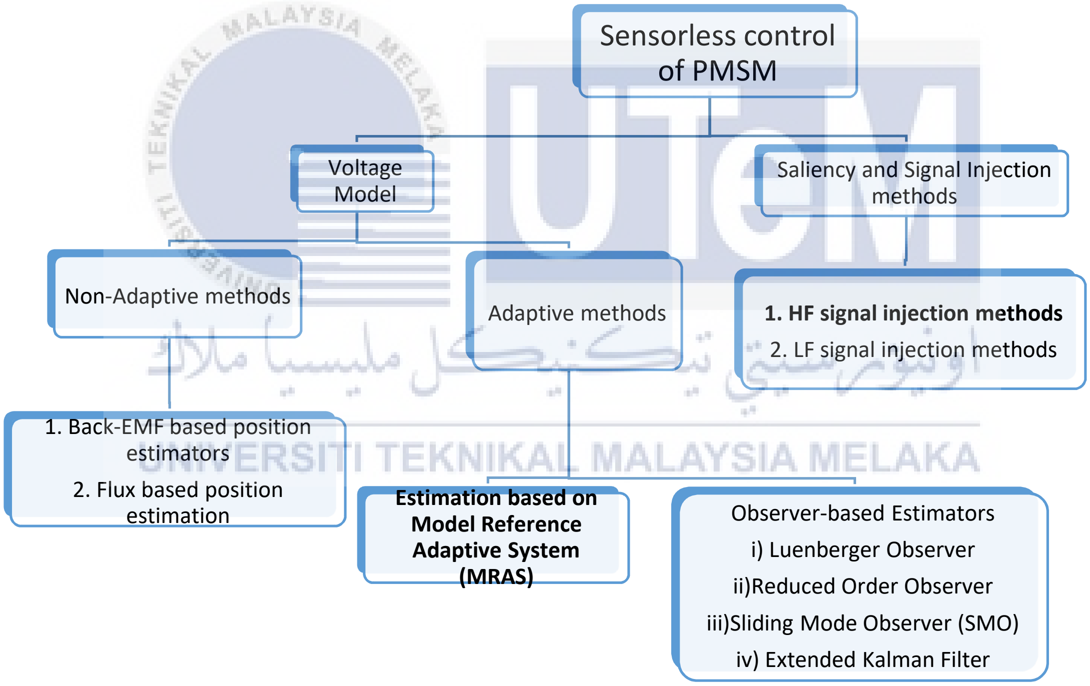

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Figure 1.1: Common sensorless control technique for PMSM[4]

Figure 1.1 presents the common sensorless control techniques in estimating the rotor position in PMSM drives. Each technique has given its own advantages and disadvantages. In this project, Model Reference Adaptive System (MRAS) has been chosen for voltage model methods. Despite, of the numerous technique have been proposed for speed and rotor position estimation, many factor remain crucial to evaluate their effectiveness such as accuracy, potential start-up failure, long convergence time and limited system stability[5].

1.2 Motivation

In the last decade, the development of sensorless control of both induction motors and permanent magnet synchronous motor has been an important research and getting increasingly sophisticated. PMSM typically used in variety of industrial application for its high performance drive system in order to replacing classic dc and induction machine drives such as CNC machine, servo drives, electric vehicle actuators, wind generation system and robotic. Plus, this motor brings a huge advantages compared to another motor such as lower rotor inertia, lower copper loss and more robust construction because of field winding of the rotor is swapped by permanent magnet[2].

For example, an automotive industry has adopted this technology in manufacturing an electric vehicles (EV) such as Toyota Prius which utilizes a PMSM. This will contribute much in the car industry in making a car that more economical and environmental friendly. For this reason, a diversity of method has been planned in order to build a reliable drive system for PMSM.

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1.3 Objective

The main objectives of this research are:

1. To develop and model a sensorless control of PMSM drive using voltage model based on Power Reactive Equation.
2. To analyze the proposed method in term of speed behavior and load disturbance by using sensorless control of PMSM drives using MRAC based on Power Reactive Model.

1.4 Problem Statement

The PMSM is a versatile motor that act as variable speed drive in many applications. PMSM is electronically commutated and this control needs rotor position information. Mostly, PMSM application comes with a mechanical sensor that act as observer or encoder in order to estimate the rotor speed. This mechanical sensor that integrate with PMSM cause many disadvantages to the system. Among them are reduce the reliability, requires extra cost, increase complexity, increase the drive size and needs a regular maintenance. In addition, this mechanical sensor is easily get damaged by mechanical impacts in an industrial environment. For this reason, this project proposed sensorless drives using voltage model based on Power Reactive Equation to overcome. The advantages of Model Reference Adaptive Control (MRAC) based on Power Reactive Equation are less sensitive to motor parameter variation, lesser computation as the straightforwardness expressions has been used, independently stator resistance and free from integrator.

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1.5 Scope

The limitation of this research are:

i) This simulation consists of development of conventional PMSM drives and sensorless control of PMSM drive using MATLAB/Simulink.

ii) The voltage model used is limited to Power Reactive Equations only.

1.6 Project Outline

This PSM report covers five chapters which are introduction, literature review, methodology, result and conclusion. For this project outline, the element of each chapter will be stated below:

Chapter 1: Introduction

Chapter 1 consists of research background, problem statement, objectives, scopes and project outline. In this chapter, problem statement is stated clearly along with relevant solution. It is important to achieve the objective of this project with the limitation of this project.

Chapter 2: Literature Review

Chapter 2 discusses about theoretical part about the PMSM drive, the types of sensorless control and reason of choosing voltage model. This chapter also describe the review of the past research and summary of the comparative study of sensorless technique.

Chapter 3: Methodology

This chapter explains about the project flow during this semester in order to complete this Final Year Project (FYP). It is containing of flowchart project, Gantt chart and simulation study.

Chapter 4: Preliminary Result

This chapter is presents the expected result with the Simulink model of the conventional PMSM drives and sensorless control of PMSM drives.

Chapter 5: Conclusion and Recommendation

Chapter 5 conclude the overall discussion of result and analysis. Plus, the recommendation of future works.

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CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter discusses the theory of PMSM drive and relative study of sensorless control technique of PMSM drive. Furthermore, this chapter gives a review of the previous studies about the PMSM drive with highlighting of the advantages and disadvantages of each technique.

2.1 PMSM Drives

Permanent Magnet Synchronous Motor (PMSM) drives is substitute of dc motor and induction motors drives and it is mainly used in industrial applications for example machine tools and industrial robots. According to Arafa S. Mohamed[1], PMSM is popular among the other types of motor due to compactness, high efficiency, simple modeling, fast dynamic response and produce high torque. The main disadvantage of a PMSM is the usage of position sensor. Other than the high cost of the position sensor, it also cause frequent maintenance, requires extra space, reduce the reliability of the drive and increase complexity[1],[2]. For these reasons, the researchers have find a new alternative method on the rejection of this position sensor at the motor shaft such as encoder or Hall effect sensor without reducing the dynamic performances of the drive.

Practically, there are two main schemes for the instantaneous torque control of high-performance variable speed drives: which are Field Oriented Control(FOC) or Vector Control and Direct Torque Control (DTC). The objective of these scheme is to control efficiently the torque and flux of the motor in order to track the rotor position.

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Table 2.1: Comparison between FOC and DTC[6]

	FOC	DTC
Transformation	Present	Void
Dynamics	High	High
Robustness	Robust	Robust
Speed sensor	Essential	Less needed
Parameter sensitivity	Large	Regular
Control close	Needed PWM	Not need PWM
Decoupling circuit	Required	Not required
Regulators	Three stator regulator	Torque regulator and flux regulator
Conduct down speed	Decent	Poor

Table 2.1 summarize the comparison between the FOC and DTC control scheme. The advantages of DTC are the nonappearance of coordinate transformations, decoupling circuit and have a high torque dynamics response [6]. In addition, DTC is not sensitive to parameters variations, does not need the rotor position and have a simple control scheme. However, this scheme have some drawbacks for example needs information of the stator flux, high torque ripples and hard to maintain torque and flux at very low speed[7]. On the contrary, FOC have better torque dynamic response and have a decent conduct down speed.

2.2 Types of sensorless technique of PMSM drives

Types of sensorless technique of PMSM drives can be classified into 2 categories which are fundamental based methods or voltage model and saliency and signal injection methods.

2.2.1 Fundamental Based Methods / Voltage Model

In estimating the rotor position and speed, fundamental based methods are mostly used in PMSM drives. These fundamental based methods are practical for medium to high speed applications. These approaches can be divided into two categories: open loop and closed loop observers. The open loop position/speed estimation methods are direct and easier to carry out. The example of open loop methods is back-EMF, flux based observer or estimators using monitored stator voltages/currents. In a closed loop observer, the error between the outputs of the plant and the observer are often used as the inputs to the observer. The observer gains are invented to force the observer output to merge with the plant output. Therefore, the estimated values of the states of interest are forced to merge to the actual values. From this perspective, the closed loop observer can be seen as an adaptive method, which has a decent disturbance rejection property and decent robustness to the variations of the machine parameters and the noises in current or voltage measurements[8]. The examples of closed loop observer are Sliding Mode Observer (SMO), Extended Kalman Filters (EKF) and Luenberger Observer.

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2.2.2 Back EMF Methods

In PMSM, the movement of magnets relative to the armature winding bases a motional EMF. The EMF is an element of rotor position relative to winding, the info of the position is gained by the EMF waveform. The estimation of the rotor position is gained by the change of the arguments of back EMF in the α-β reference frame and the difference of the arguments in rotating d-q frame. This method is simple, fast and direct without using complex observers. However, the execution of this strategy is subjected to the exactness of the detected current or voltage of the machine parameters.

2.2.3 Flux Based Position Estimation

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At steady state, the stator and rotor flux vectors are synchronously rotate. Thus, the stator flux angle and the rotor flux can be calculated and determined. The exactness of the flux based position estimation are hugely depending on the quality and accuracy of the voltage and current measurements. According to Jongwon Choi, Kwanghee Nam and Alexey A. Bobtsov[9]. The types of voltage model used is flux observer in the stationary frame. This types of sensorless control is like a Luenberger type observers for the voltage equation whereas the speed information is not used. Since integrators are required in this process, the initial condition of the integration and current sensor DC offset are issue that need to handled properly. So, the rotor flux observer was modified by incorporating a negative gradient of the parameter error by linked the parameter estimation algorithm to the observer dynamic. However, the performance of transient response is usually unsatisfactory, but it works well in the steady state

2.2.4 Model Reference Adaptive System (MRAS)

The MRAS technique uses discontinuous control for estimate rotor position angle created on a stator current estimator. This technique is quite simple, good stability and not require a high computation power. This is because MRAS only measures stator currents in a PMSM drive. In addition, this technique is quite steady and strong because it removes the steady state error created in the alteration of the speed [1],[7],[10].

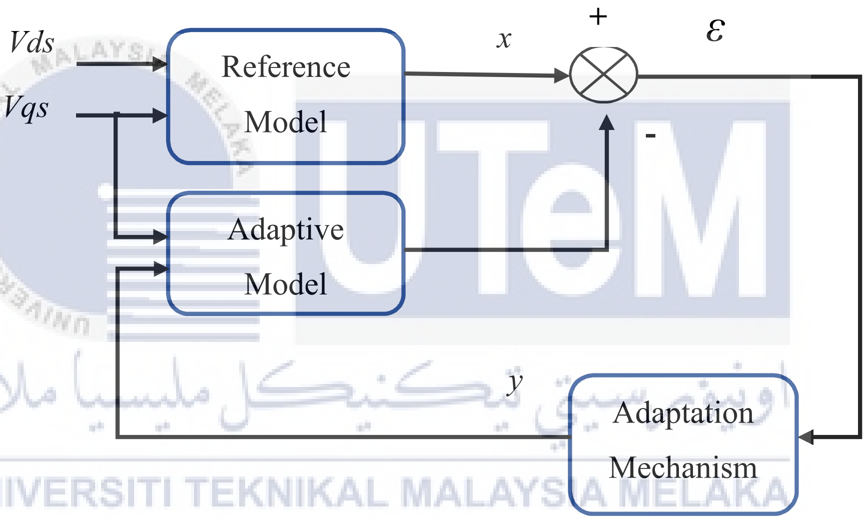

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Figure 2.1: Rotor speed estimation structure using MRAS[7]

Figure 2.1 presents the block diagram for rotor speed estimation structure using MRAS. The MRAS technique used comparison between two outputs of two estimators. The first one is called model reference and the second one is adaptive model. The error between two estimators are compared and feed to an adaptive mechanism to generate the rotor speed or position.

2.2.5 Extended Kalman Filter

Basically, EKF is filter the noises in measurement and inside the system. It's an optimum for filtering method to nonlinear system. The advantages of EKF is excel with speed performance, excel with low noise immunity, decent dynamic response and decent steady state regulation. But, EKF also has a major drawback which are long computation time, hard to implement, not robust to motor parameter variation and complex algorithm[1],[11].

2.3 Saliency and Signal Injection Methods

In this methods, a high frequency voltage or current signal is injected to gain currents harmonics that consists rotor position. This method has a better performance to estimate the rotor position in low speed or standstill compared to other sensorless control scheme[1]. The idea behind sensorless estimation scheme using saliency methods is because the inductance winding of machine is benefits to the rotor position due to saliency. So, the rotor position can be figure out from the inductance variation profile. But, this method also come with some drawback in term of complexity for real time implementation and less portable from one machine to another[1]. Diverse of high frequency signal injection schemes has been reported in the literature can be classified as continuous signal injection, transient signal injection and PWM excitation.

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According to Ravikumar Setty and Shashank Wekhande[12], the high frequency signal injection technique can be categories into continuous signal injection technique, high frequency signal embed on to PWM and transient signal injection technique. In continuous high frequency voltage injection, the resultant current signal is very effective for estimate the rotor position is placed in the large stator current and other high frequency components. In order to have better estimation result and easier demodulation, the amplitude of the injected voltage signal should larger enough. The amplitude of the injected voltage signal is proportional to Signal to Noise Ratio (SNR). However, the torque ripple and the noise will amplify if the injected signal is increased.

Olfa Bel Hadj Brahim, Houda Ben Attia Sethom and Hafedh Sammoud [13],high frequency injection technique is considered in the estimated rotor reference frame (d,q) in order to get rotor position error information. The result shows that rotor position estimation is not sufficient enough to carry high performance due to low amplitude of the high frequency current. In order to increase the rotor position estimation performance a modified demodulation of the high frequency current resulting from injection was recommended by using a high pass filter amplifier and was employ to measure PMSM current. For this function, a high pass filter amplifier has been used to draw out the q-axis current and to magnify it, before the demodulation of the high frequency q-current component. The experimental results show that the improvement at standstill of rotor position error separation compared to a conventional scheme.

According to Sang-II Kim, Jun Hyuk Im and Rae-Young Kim[14], the extraction of rotor information from the relation between injection voltages and induced current in the high frequency voltage model of an IPMSM established on the high frequency rotating voltage signal injection in the stationary reference frame. The rotor position is calculated from the obtained current by transforming the rotation matrix in the stationary reference frame and by the envelope of induced current through the all pass filter. Not alike, the conservative heterodyning demodulation process, the proposed method produced the accurate rotor position of the band pass filter or low pass filter.

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2.4 Review of Previous Related Work.

This section will discuss the comparison of several methods of sensorless control of PMSM drives using voltage model. According to Raihana Mustafa, Zulkifilie Ibrahim and Jurifa Mat Lazi[15], show the simplified mathematical model of the PMSM by performing a V-I model based Model Reference Adaptive Control (MRAC) to eliminate the use of speed sensor. This technique has been recognized widely due to its straightforwardness and good stability. In addition, this technique does not require extra hardwire or signal injection like EKF and ELO. Results show that the rotor estimated speed is produced from the adaptation mechanism using the elimination of error between the estimated value gained in the two models of voltage and current. The simulation results show it has a good response in the low and high speeds.

Ameur Aissa, K. Ameur and B. Mokhtari [7] presents, the sensorless Direct Torque Control (DTC) based on MRAS algorithm and PI with adaptive gains Fuzzy Logic. The used of DTC is because of good torque dynamic response and not sensitive to parameters variations except stator resistance. The MRAS is utilized to estimate speed and stator resistance and compensate the effects of parameter variation on stator resistance variation introduce errors flux and torque estimation and affect the performance. On the hand, PI speed controller with two adaptive Fuzzy Logic is investigated and compared with conventional PI controller. The results obtained shows the satisfactory in terms of estimation errors, robustness and good stability with any drive electrical system for different operating conditions.

According to Marian Tarnik and Jan Murgas [16], the estimation of disturbances caused by the variation of electromagnetical parameters can be also used for torque ripple minimization. The design current adaptive controller and the speed adaptive controller are independent and they can be combined with the non-adaptive controllers. However, the adaptive gain or the auxiliary filters parameter are still searching for the appropriate values and may be difficult and depends on the particular case.

Kang Jinsong and Zeng Xiangyun [17] proposes a self-adaptive law based on Popov theory. The proposed MRAS of PMSM is not sensitive to the initial position of the rotor which means the motor can be start up wherever the rotor position is located. This method proposed self-adaptive of PI controller, and to reduce overshoot and make the system stable, it should

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reduce the coefficient of the PI controller. As the motor has been start up, the PI controller should be increased to decrease the steady state error. As result, this method provides a high precision in speed estimation, low steady state error and capable of anti-jamming with load interference.

Table 2.2 presents the summary of previous study of sensorless control of PMSM drives. Based on the literature survey as discussed above, this current project aims to develop a stable sensorless control of PMSM drives using voltage model. The voltage model is suitable for middle and high speed range. The types of voltage model used is Model Reference Adaptive Control (MRAC) based on Power Reactive Equation. The advantages of this method are low sensitive with motor parameter, low computational time, using simplified mathematical equation and reliable in high and middle speed range. It also free from integrator problem and do not required hardware complexity.

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Table 2.2: Previous study of sensorless control of PMSM drives

Authors	Methods	Contribution	Results
Ameur Aissa, K. Ameur and B. Mokhtari [7]	Sensorless Direct Torque Control (DTC) based on MRAS algorithm and PI with adaptive gains Fuzzy Logic	Using DTC because of good torque dynamic response and not sensitive to parameters variations. PI speed controller with two adaptive Fuzzy Logic is investigated and compared with conventional PI controller	Shows the adequate performance in error estimation and good stability with any drive electrical system with different operating conditions.
Marian Tarnik and Jan Murgas [16]	Model Reference Adaptive Control of Permanent Magnet Synchronous Motor	Estimation of disturbances caused by the variation of electromagnetical parameters can be also used for torque ripple minimization. The design current adaptive controller and the speed adaptive controller are independent and they can be combined with the non-adaptive controllers.	Adaptive gain or the auxiliary filters parameter are still searching for the appropriate values and may be hard and rely on some case.
Raihana Mustafa, Zulkifilie Ibrahim and Jurifa Mat Lazi[15]	Adaptive Speed Control of Sensorless PMSM Drives	Simplified mathematical model of the PMSM by performing a V-I model based Model Reference Adaptive Control (MRAC) to remove speed sensor.	The estimation of rotor produced from the adaptation mechanism using the elimination of error between the estimated value gained in the two models of voltage and current

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Kang Jinsong and Zeng Xiangyun [17]	Self-adaptive of sensorless control of PMSM based on MRAS	Proposed self-adaptive of PI controller, and to reduce overshoot and make the system stable. This methods does not depends to any parameter, so it’s more robust and suitable for low frequency application.	This method provides a high precision in speed estimation, low steady state error and capable of anti-jamming with load interference.

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CHAPTER 3

METHODOLOGY

3.0 Introduction

This chapter discusses the methodology of the project. The discussion of this project will deeply describes show this project is being handled according to the guided timeline. This chapter also covers the procedure of simulation and research background of this project.

3.1 Flowchart of Methodology

Figure 3.1 demonstrates the overall flow of this project. The project starts with modelling the standard PMSM drives by using sensor. The modelling of PMSM drives will then be simulated using the MATLAB/Simulink. Then, this standard PMSM will be analyzed to validate the results. Troubleshooting is required for this simulation in order to get a better result. Next, this simulation will be continued with the modelling of PMSM drives by using sensorless technique which is MRAC (Model Reference Adaptive Control) based on Power Reactive Equation. This type of voltage model was simulated and analyzed to have a better understanding in term of speed behavior and load disturbance.

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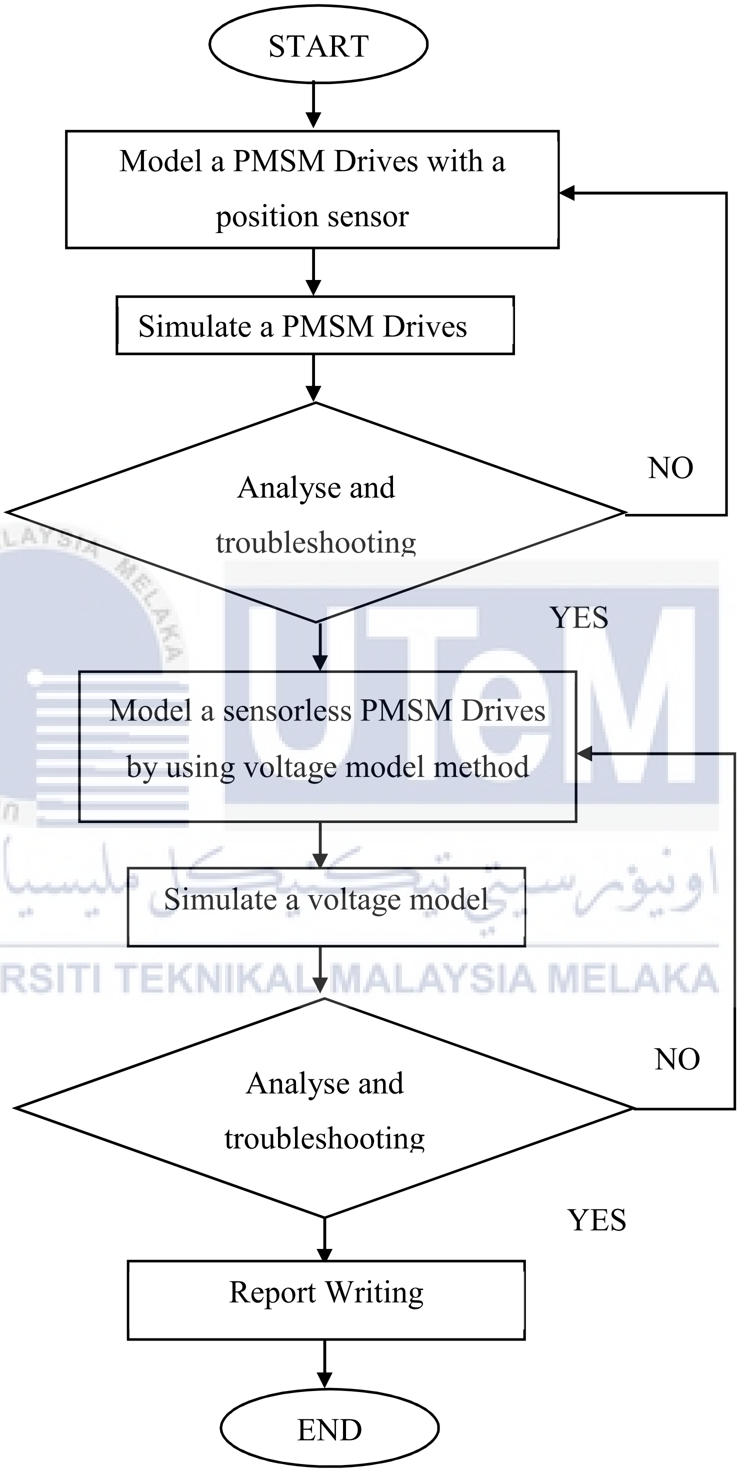

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Figure 3.1: Flowchart of project process

3.2 The Development of Standard PMSM Drives

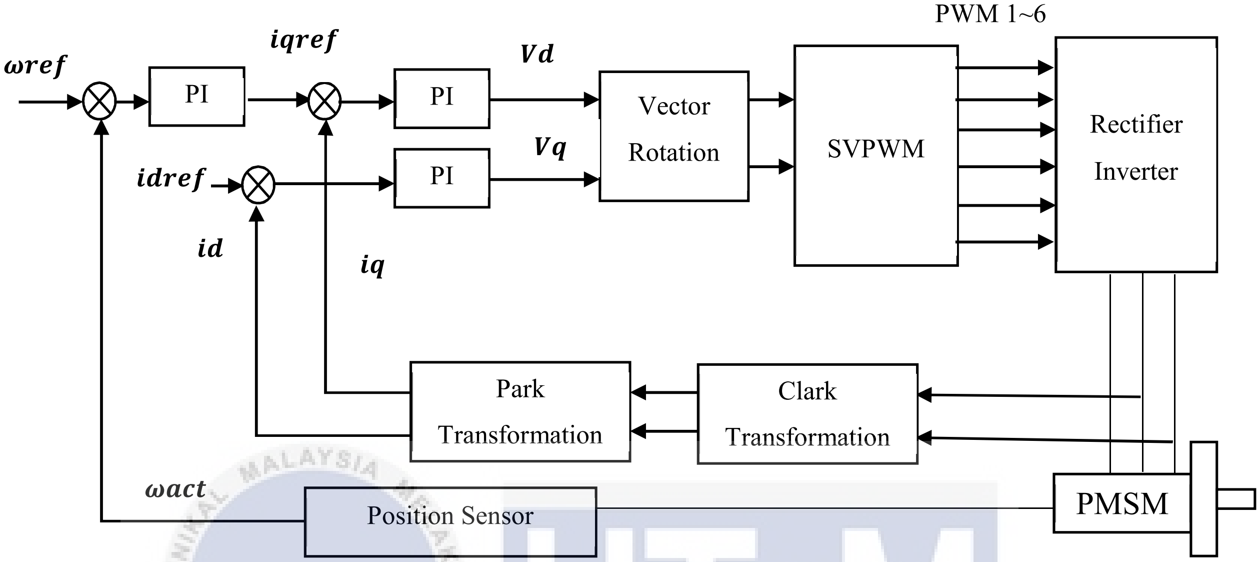

Figure 3.2: Block diagram of PMSM drives[18]

Figure 3.2 demonstrates the overall block diagram of PMSM drives with sensor in estimation the rotor position. In this control system, the deviation between reference speed and actual speed were compared and regulated through PI speed controller. The error between I_{sqref} and I_{sdref} are go through the PI current controlled and the respectively output phase voltage V_{sqref} and V_{sqref} on the d-q rotating coordinate. These V_{sqref} and V_{sdref} are transformed from d-q rotating reference frame into α-β stationary reference frame through Inverse Park transformation. $V_{s\alpha ref}$ and $V_{s\beta ref}$ are transformed into a three phase stationary reference frame by using Inverse Clarke transformation. These *Va, Vb* and *Vc* were inserted voltage space vector PWM technique to produce PWM signal in order to control the inverter. The output of inverter: *Ia* and *Ib* are transformed through Clarke and Park transformation into I_q and I_d components as the negative feedback.

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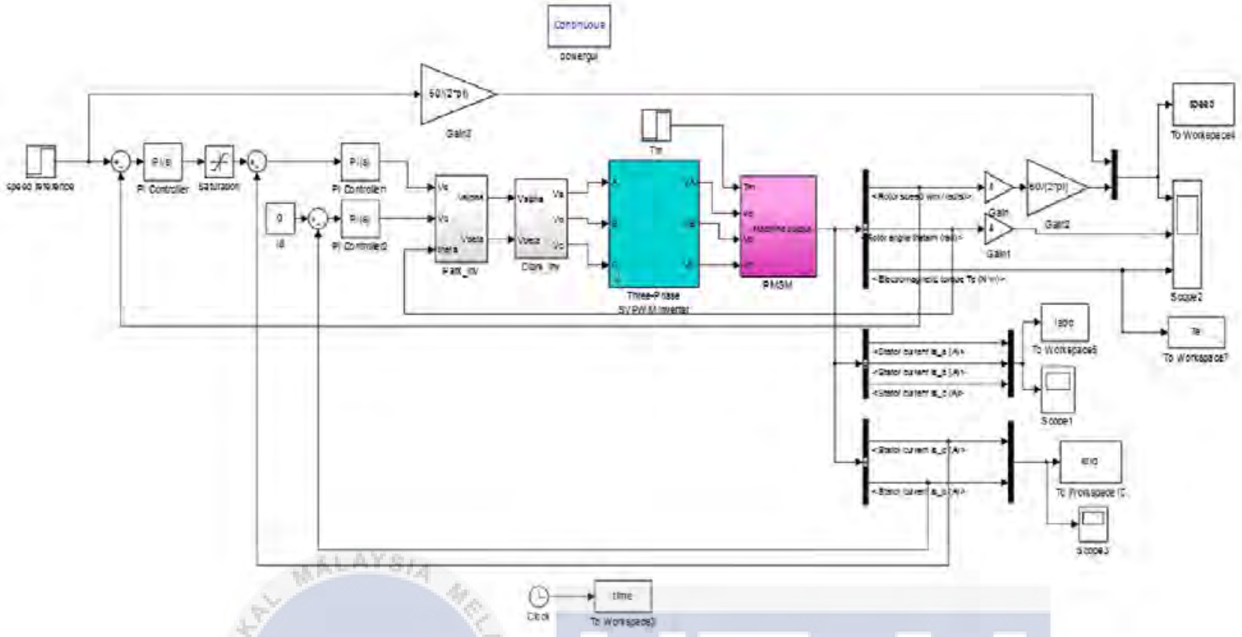

Figure 3.3: Overall modelling diagram of standard PMSM drives

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Figure 3.3 shows the overall block diagram of standard PMSM drives. Basically, the modelling of PMSM Drives consists of three main parts which are speed control of PMSM, three phase inverter and d-q PMSM model. The explanation of these three part will discuss in subchapter below.

3.2.1 Speed Control of PMSM

The PI controller applied in this paper are speed control loop and current control loop. This controller consists of a proportional gain (Kp) and integration gain (Ki). The aim of speed control is to drive the motor respect to input of speed reference. This is because this controller is most usually used approaches in the industry and it’s much easier to analyzed mathematically. The block diagram for a PI controller is presented in Figure 3.4 below.

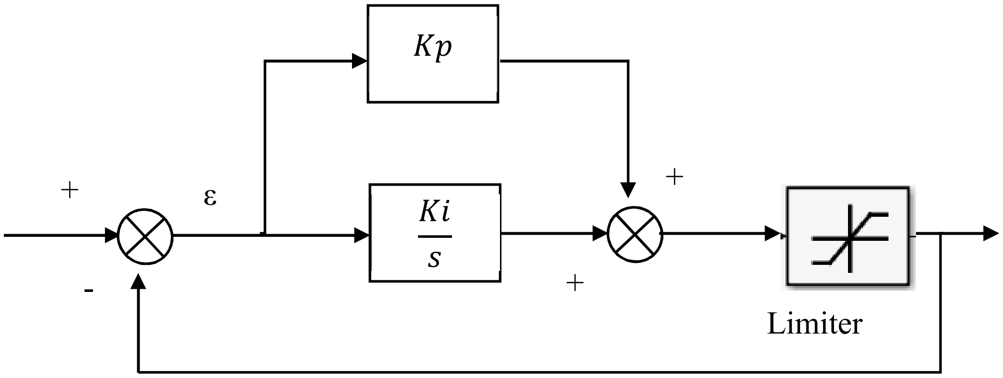

Figure 3.4: PI Controller

Speed controller analyses the difference between the reference speed and the actual speed producing an error, which is fed to the PI controller. Then, error signal ε is circulated to the controller gains which are Kp and Ki. The limiter is used as limiter and will limit the overshoot current or undershoot current in the range of rated value. The value of limiter used is 10 for upper limit and -10 for lower limit.

Basically, speed control of the PMSM contains of two loops, which are inner for current and the outer loop for speed. Usually, the configuration of speed loop is considered 10 times slower than the current loop.

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The gains for the PI controller in the current loop are:

$$Kp = 2\xi \omega n L - R \tag{3.1}$$

$$Ki = \omega^2 L \tag{3.2}$$

$$Kt = \frac{3}{4} P\psi m \tag{3.3}$$

And the gains for the PI controller in the speed loop are:

$$Kp = \frac{2\xi \omega n - B}{Kt} \tag{3.4}$$

$$Ki = \frac{\omega^2 J}{Kt} \tag{3.5}$$

From the equations above, the current loop and speed loop gains are used just for simulation and experimental set-up. However, to achieve the best results these gains is recommended to alter manually.

3.2.2 Three Phase Inverter

Three phase inverter is used to produced three phase voltage supply to the motor. The input of inverter is in DC voltage and six switching signals. These six switching signal can be performed by using Space Vector Pulse Width Modulator (SVPWM). So, SVPWM needs input from the stationary orthogonal reference frame voltages, $\boldsymbol{V\alpha}$ and $\boldsymbol{V\beta}$. These stationary orthogonal reference frame voltages is get from moving reference frame voltages $\boldsymbol{Vds}$ and $\boldsymbol{Vqs}$. This can be done by using Park Inverse transformation and Clarke Inverse transformation.

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Park Inverse transformation is used to transform d-q axis rotating reference frame into two-axis orthogonal α-β stationary reference frame. The Inverse Park transformation can be determined by the following equations:

$$V\alpha = Vd * \cos(\theta) - Vq * \sin(\theta) \tag{3.6}$$

$$V\beta = Vq * \cos(\theta) + Vd * \sin(\theta) \tag{3.7}$$

Clarke Inverse transformation is used to transform two-axis orthogonal α-β stationary reference frame into a three phase stationary reference frame. The equation of Inverse Clarke transformation is stated below:

$$Va = V\alpha \tag{3.8}$$

$$Vb = \frac{-V\alpha + \sqrt{3} * V\beta}{2} \tag{3.9}$$

$$Vc = \frac{-V\alpha - \sqrt{3} * V\beta}{2} \tag{3.10}$$

SVPWM is used generate PWM switching signal from three phase stationary reference frame. The parameter of Vdc in this simulation is 370V. SVPWM can be determined by following equation:

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$$Va *= \frac{Vdc}{6}(2Sa - Sb - Sc) \tag{3.11}$$

$$Vb *= \frac{Vdc}{6}(2Sb - Sa - Sc) \tag{3.12}$$

$$Vc *= \frac{Vdc}{6}(2Sc - Sa - Sb) \tag{3.13}$$

3.2.3 d-q PMSM Model

Clarke transformation is used to transform three phase current quantities and translate that to the two-axis α-β orthogonal stationary reference frame. The equation of Clarke transform can be determined below:

$$I\alpha = \frac{2}{3}\,(Ia) - \frac{1}{3}\,(Ib - Ic) \tag{3.14}$$

$$I\beta = \frac{2}{\sqrt{3}}\,(Ib - Ic) \tag{3.15}$$

Park transformation is used to convert from two-axis α-β orthogonal stationary reference frame into d-q rotating reference frame. The equation of Park transform can be determined by following equation:

$$Id = I\alpha * \cos(\theta) + I\beta * \sin(\theta) \tag{3.16}$$

$$Iq = I\beta * \cos(\theta) - I\alpha * \sin(\theta) \tag{3.17}$$

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3.3 The Development of Sensorless PMSM Drives

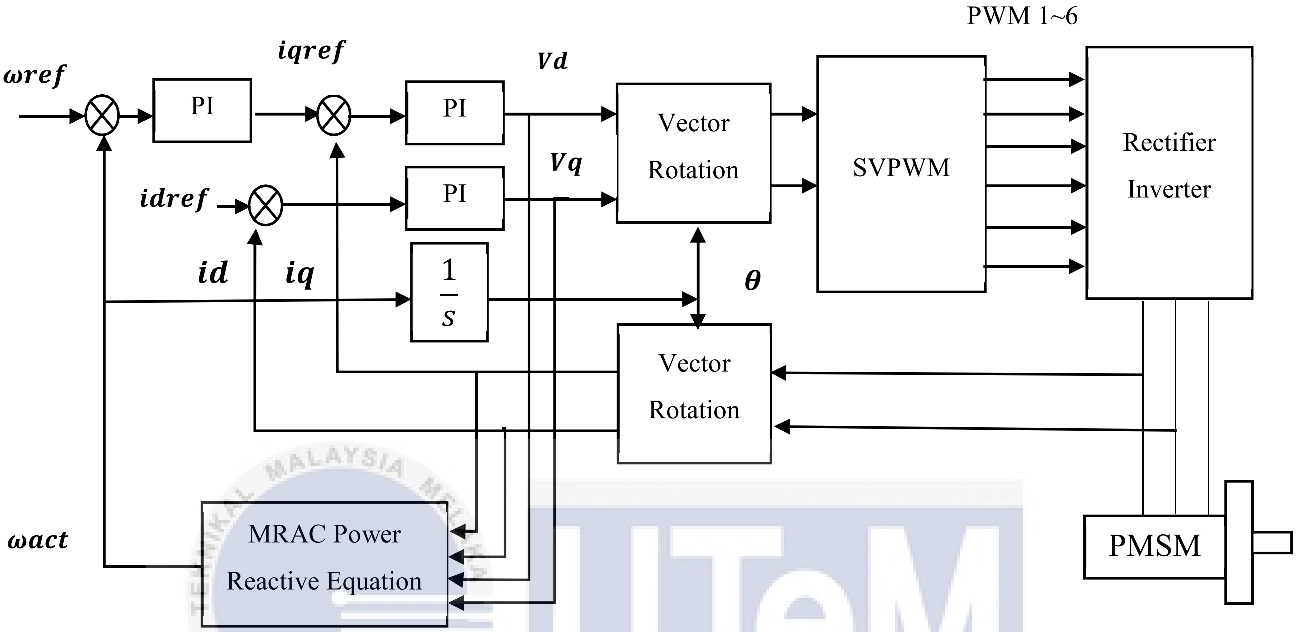

Figure 3.5: The block diagram of sensorless PMSM drives based on MRAC Power Reactive Equation

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Figure 3.6 demonstrate the overall modelling diagram of sensorless PMSM Drives by using voltage model which is MRAC based on Power Reactive Model. It's separated by four main section which are controller, three phase inverter, d-q PMSM Model and MRAC. The controller consists of PI speed controller and PI current controller. This type of controller is utilized because of it's easier to apply to motor and not sensitive to modeling errors.

Three phase inverter generate three phase voltage supply to the motor. The input of the inverter is DC voltage and six switching PWM signals. This could be done by using space vector pulse width modulator (SVPWM). Then, SVPWM requires the stationary orthogonal reference frame voltages,$V\alpha, V\beta$ as the input from the moving reference frame voltages, Vd, Vq by using inverse Park's transformation.

d-q PMSM Model is a mathematical model that used to form the d-q permanent magnet synchronous motor model. The output PMSM motor is used as input to the MRAC. MRAC is design as speed estimator without using sensor. This model contains of three parts which are reference model, adjustable model and adaptive mechanism. The output of MRAC will produce the actual speed and compared to reference speed. The actual speed component also be fed to vector control after it has be convert by integrator as theta, θ.

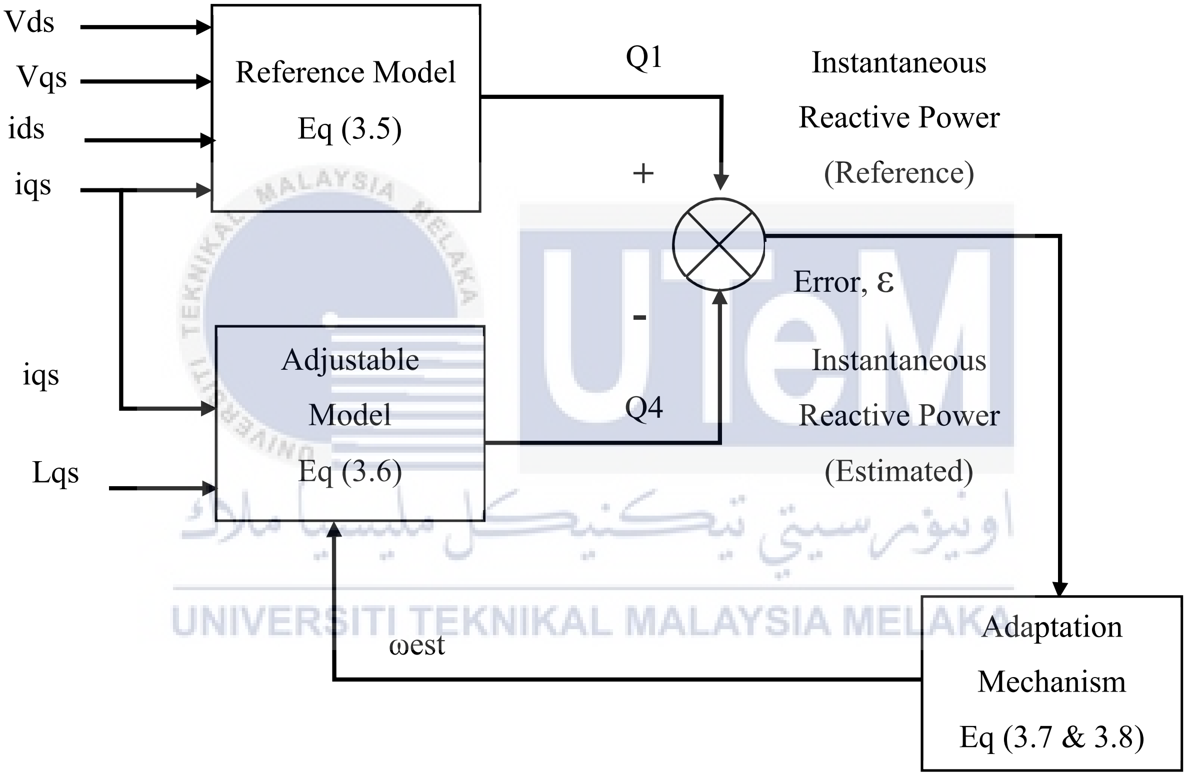

Figure 3.6: Block Diagram of MRAC based Power Reactive Equation

Figure 3.6 demonstrates the block diagram of MRAC based Power Reactive Equation. MRAC model contains of three main parts which are reference model, reference model and adaptation mechanism model. In order to estimate the rotor, position the reference model and adjustable model were compared to produce error signal. Then, the error signal is fed into the PI controller which represent adaptation mechanism. This output signal is tuned until the zero error. The formula of MRAC based on Power Reactive Equation are stated in (3.18) to (3.21) below.

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Reference Model:

$$Q1 = Vqs\ ids - Vds\ iqs \tag{3.18}$$

Adjustable Model:

$$Q4 = \omega m\ Lqs\ i^2qs \tag{3.19}$$

Power Reactive Model:

$$\varepsilon = Q1 - Q4 \tag{3.20}$$

Adaptation Mechanism:

$$\omega_{est} = (Kp + \frac{Ki}{s})\varepsilon \tag{3.21}$$

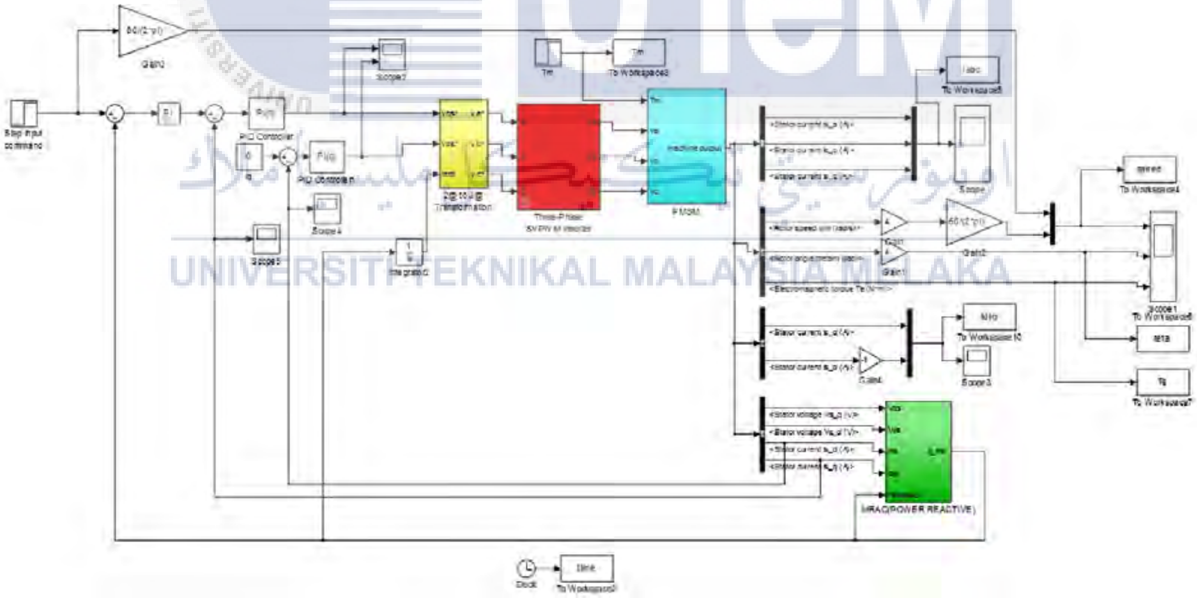

Figure 3.7: Overall modelling diagram of sensorless PMSM Drives by using voltage model

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3.4 Gantt Chart

Table 3.1: Gantt Chart

Milestone	Year	2016				2017				
	Month Task	9	10	11	12	1	2	3	4	5
1	Model a standard PMSM drives		■	■	■					
2	Simulate a PMSM drive					■	■			
3	Model a fundamental voltage model						■	■		
4	Simulate a voltage model							■	■	
5	Report writing			■	■	■	■	■	■	■

Table 3.2 shows the Gantt chart of the project timeline. Based on Gantt chart above, the overall project only covers the development of controlling PMSM drive by using sensor and in comparison with sensorless control of PMSM drive by using voltage model in order to estimate rotor position. Then, both method will then be modeled and simulated with MATLAB/ Simulink. After that, the result will be analyzed and discussed in the report.

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CHAPTER 4

RESULT AND DISCUSSION

4.0 Introduction

This chapter provides the comparative simulation results of PMSM drives by using position sensor and without position sensor. At first the result of PMSM drives by using position sensor will be presented, then it will be compared to sensorless control of PMSM by using combination of voltage model based on Power Reactive Equation. The drives are simulated based on three different speed references operations which are 2000 rpm, 1000 rpm and 500 rpm with different applied torque at t=0.2sec.

4.1 PMSM Drives Using Sensor

The simulation model of PMSM drives is conducted by using MATLAB/Simulink. The parameter of motor is included in Table 3.1. The inverter input DC voltage is 370Vdc. The type of rotor used in PMSM drives is round rotor. The solver used is Order 45(Dormand-Price). All the settings of motor are fixed using the stated values for all simulation studies in Table 4.1 below. The gain parameter of speed controller and current controller were shown in the Table 4.2 below.

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Table 4.1: Motor Specifications

No.	Motor Specifications	Values
1	Stator Resistance , Rs	0.9585Ω
2	Inductance , Ls	0.00525 H
4	Number of pole pairs, p	4
6	Permanent magnet flux, ψpm	0.1827 V.s
7	Torque constant, Kt	1.0962 Nm
8	Inertia, J	0.0006329 kg.m^2
9	DC link voltage	300 V
10	Rated speed	2000rpm

Table 4.2: Controller Specification

No.	Controller Specifications	Values
1	PI Speed Controller	$Kp = 2, Ki = 20$
2	PI Current Controller (iq)	$Kp = 5, Ki = 50$
3	PI Current Controller (id)	$Kp = 5, Ki = 50$
4	Switching frequency of SVPWM (fs)	10kHz

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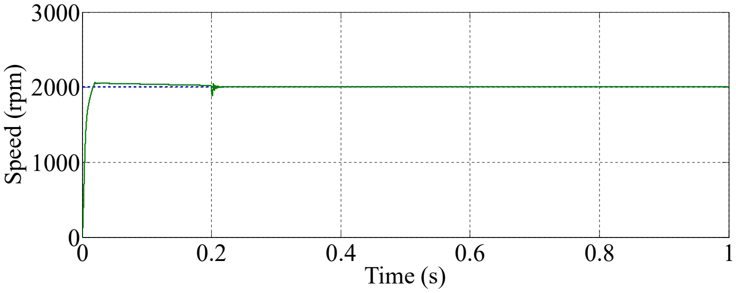
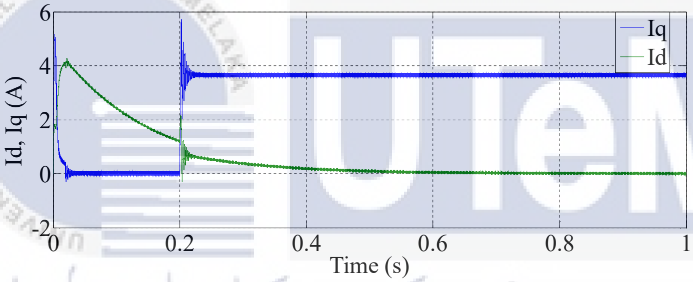
4.1.1 Speed Variation

A .2000RPM with 4Nm



(a)



(b)

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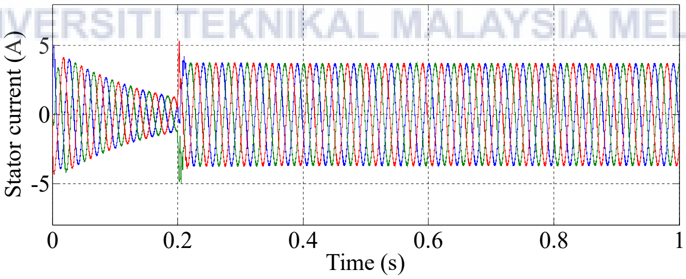

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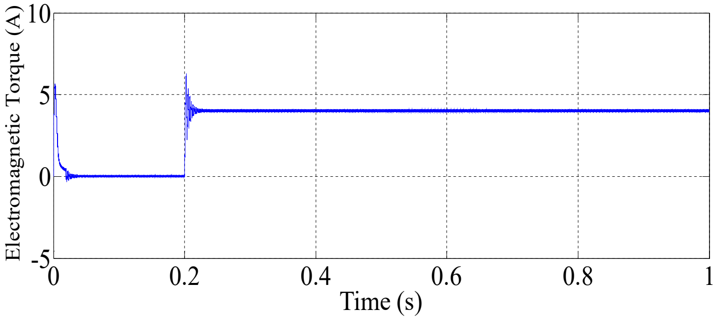

(d)

Figure 4.1: PMSM drives response for 2000rpm. (a) speed response, (b) Direct and quadrature currents, (id,iq) (c) Three phase current,(Ia, Ib, Ic) (d) Electromagnetic Torque (Nm)

From the Figure 4.1, the reference speed used is 2000rpm and the load torque, T_L= 4Nm was applied at $t = 0.2s$. The undershoot during load disturbance is about 1880rpm while for the overshoot during start-up is about 2058rpm. The rise time for this response is 0.01s and for peak time is 0.0197s.

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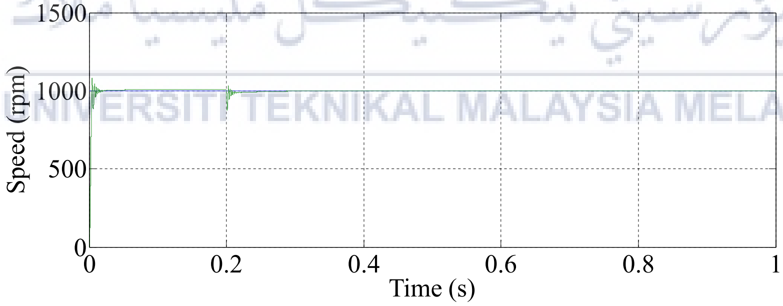
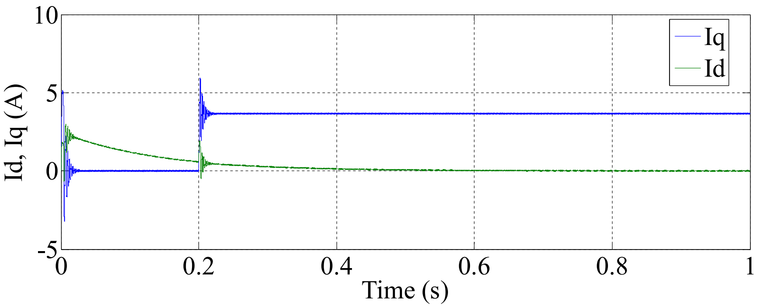
B. 1000rpm with 4Nm



(a)



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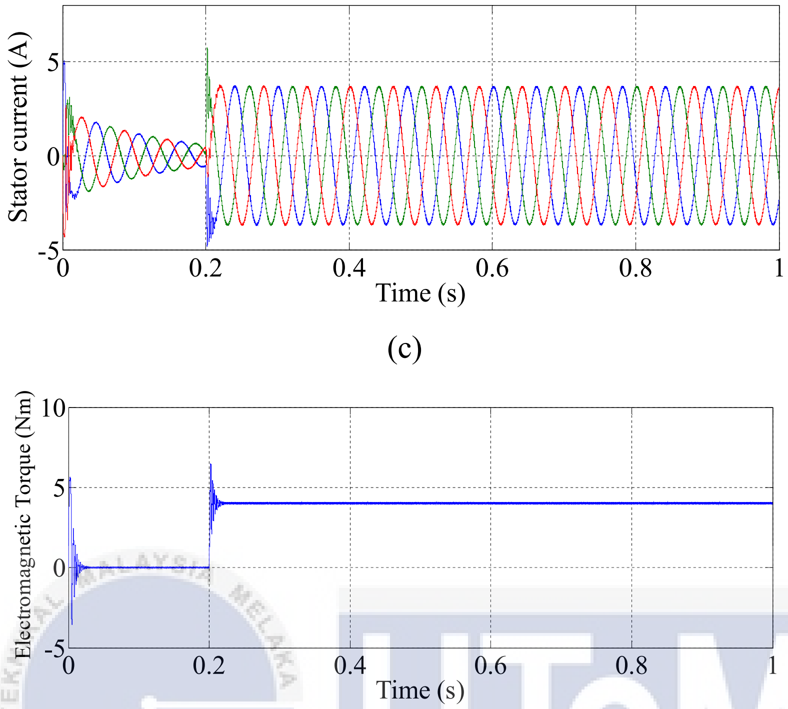

(c)

(d)

Figure 4.2: PMSM drives response for 1000rpm. (a) speed response, (b) Direct and quadrature currents, (id,iq) (c) Three phase current,(Ia, Ib, Ic) (d) Electromagnetic Torque (Nm)

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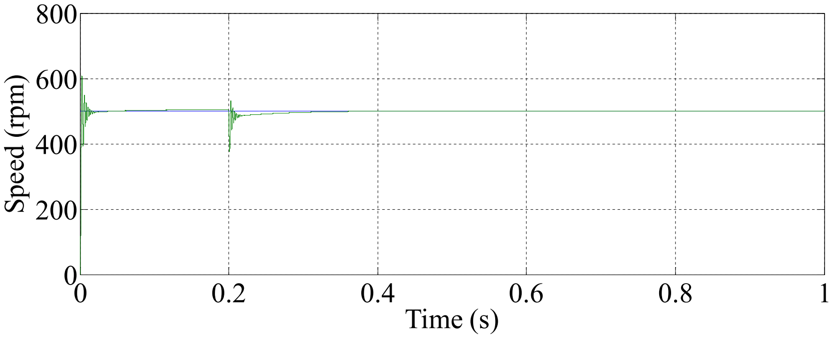
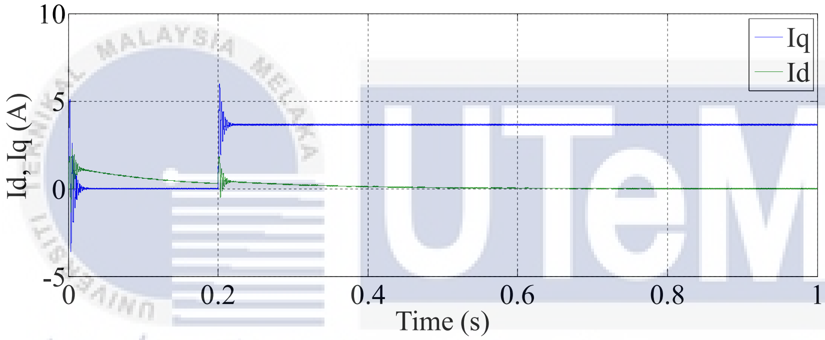
From Figure 4.2, the reference speed used is 1000rpm and the load torque, T_L= 4Nm was applied at $t = 0.2s$. The undershoot during load disturbance is about 877rpm while for the overshoot during start-up is about 1082rpm. The rise time for this response is 0.00311s and for peak time is 0.0043s.

C. 500rpm with 4Nm



(a)



(b)

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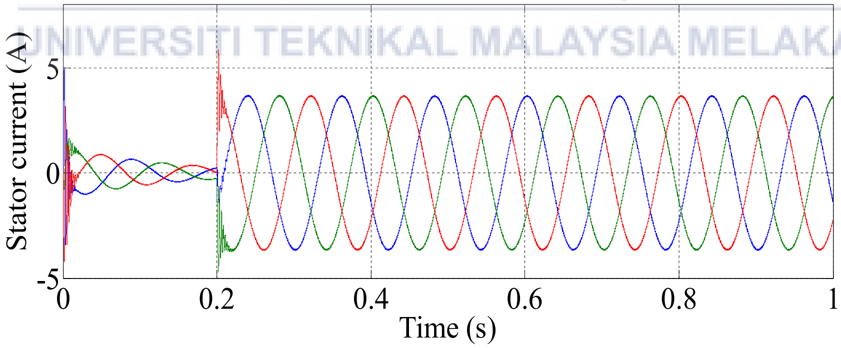

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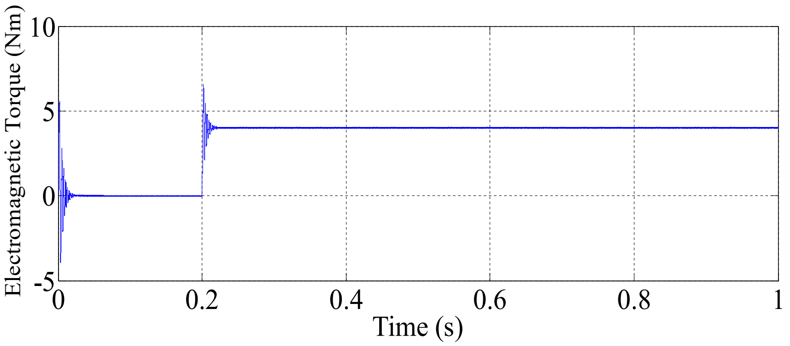

(d)

Figure 4.3: PMSM drives response for 500rpm. (a) speed response, (b) Direct and quadrature currents, (id,iq) (c) Three phase current,(Ia, Ib, Ic) (d) Electromagnetic Torque (Nm)

From the Figure 4.3, the reference speed used is 500rpm and the load torque, T_L= 4Nm was applied at $t = 0.2s$. The undershoot during load disturbance is about 376rpm while for the overshoot during start-up is about 607rpm. The rise time for this response is 0.00185s and for peak time is 0.00258s.

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4.1.2 Discussion of Speed Variation of PMSM Drives with Sensor

The result from Figure 4.1 to Figure 4.3 show only the variance of speed for 2000rpm, 1000rpm and 500rpm at the rated torque only. Results show the three phase current and quadrature current,iq is also approximately close to the torque applied while for direct current,id for all speed range is 0A, since the initial condition in simulation is zero. While the This value can be supported by the formula of electromagnetic torque stated below:

$$Te = \frac{3}{2} P \, [\Psi m \, iq + (Ld - Lq) id \, iq] \tag{4.1}$$

In term of time response characteristics, the rise time for 2000rpm is 0.01s while for the 500rpm is 0.00185s. It shows the rise time is increase as the speed is decrease. Rise time, Tr can be defined as the time for the waveform to go from 10% to 90% of its final value. Long rise time will result in slow response to the controller thus short rise time is usually compulsory.

For the settling time, Ts is defined as the time for the response to reach and stay within, 2% of the its final value. The settling time for 2000rpm is a little bit faster if compared to 1000rpm and 500rpm. This can be concluded that the settling time is increasing as the speed is decrease. Since, the relationship between settling time and percent overshoot is proportional to each other. Percent overshoot is defined as the amount that the waveform overshoots the steady state or final value at the peak time. This shows the percent overshoot at 2000rpm is lower compared to 1000rpm and 500rpm.

Peak Time, Tp is defined the time required to reach the first or maximum peak. From Table 4.3, it shows the peak time is increasing as the speed is decrease.

Table 4.3 below summaries the rise time, peak time, settling time and percent overshoot for the above results. From the table above, rise time, peak time, and settling time are slightly decrease as the speed is decrease. However, settling time for 500rpm is little bit slower to settle compared to 2000rpm and 1000rpm. On the hand, the percent overshoot is increase as the rise time is increase. This is because the overshoot is proportional to rise time.

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Table 4.3: Time response characteristics for standard PMSM

Speed	Rise time, Tr	Settling time, Ts	Peak time, Tp	Percent overshoot (%)
2000rpm(6Nm)	0.01000	0.093	0.01970	2.9
2000rpm(4Nm)	0.01000	0.093	0.01970	2.9
2000rpm(2Nm)	0.01000	0.093	0.01970	2.9
1000rpm(6Nm)	0.00311	0.010	0.00430	8.2
1000rpm(4Nm)	0.00311	0.010	0.00430	8.2
1000rpm(2Nm)	0.00311	0.010	0.00430	8.2
500rpm (6Nm)	0.00185	0.112	0.00258	21.4
500rpm (4Nm)	0.00185	0.112	0.00258	21.4
500rpm(2Nm)	0.00185	0.112	0.00258	21.4

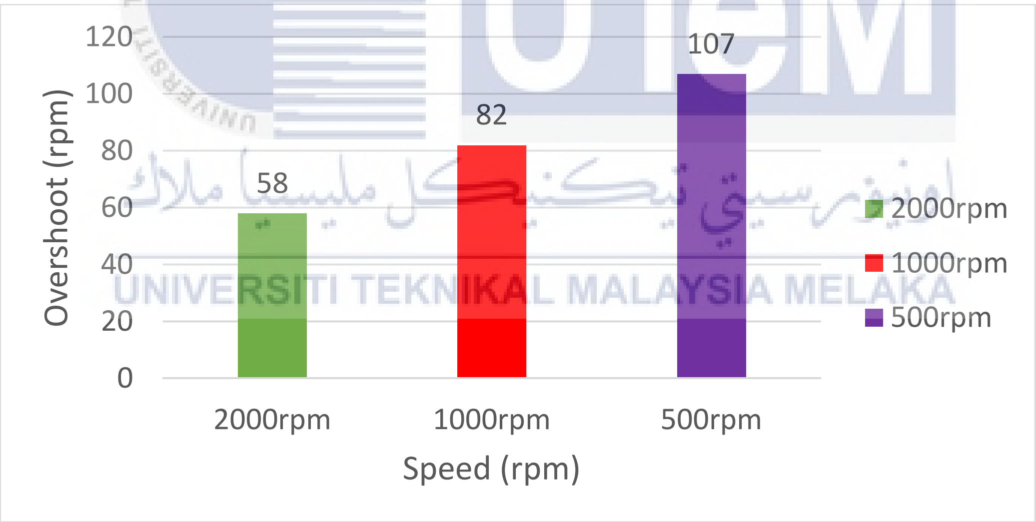

Figure 4.4: Overshoot against speed

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4.1.3 Load Disturbance

This subchapter discusses undershoot characteristics of a standard PMSM drives of three different speed reference which are 2000rpm, 1000rpm and 500rpm. The applied torque used are 6Nm, 4Nm and 2Nm at t=0.2sec.

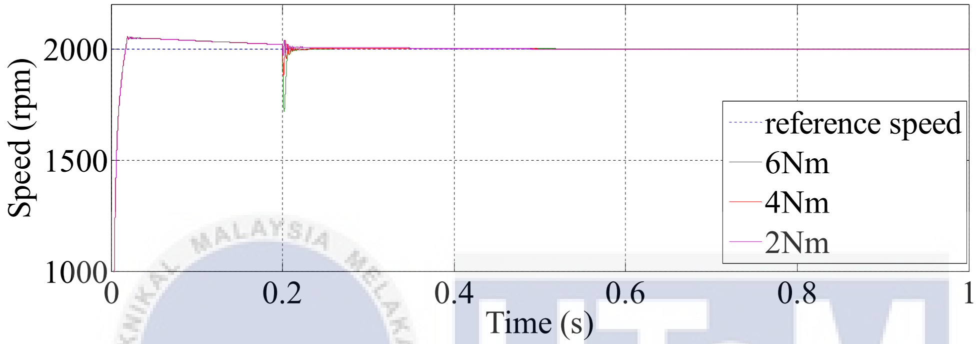

Figure 4.5: Speed (2000rpm) against the time

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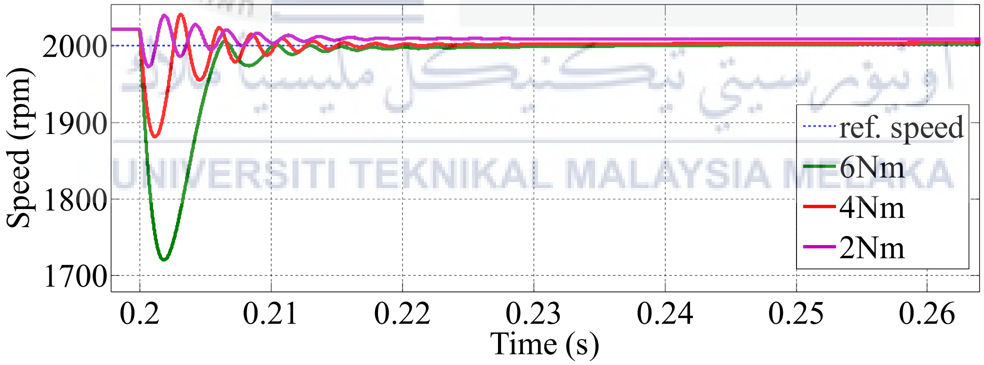

Figure 4.6 : zoomed view of undershoot for speed response 2000rpm

Figure 4.6 shows the speed response respect to the variance of input torques. The 2000rpm of PMSM was simulated with 6Nm, 4Nm and 2Nm of torque. From Figure 4.6, the speed dropped of 2000rpm are 280rpm, 120 and 27rpm with applied torque at 6Nm, 4Nm and 2Nm respectively.

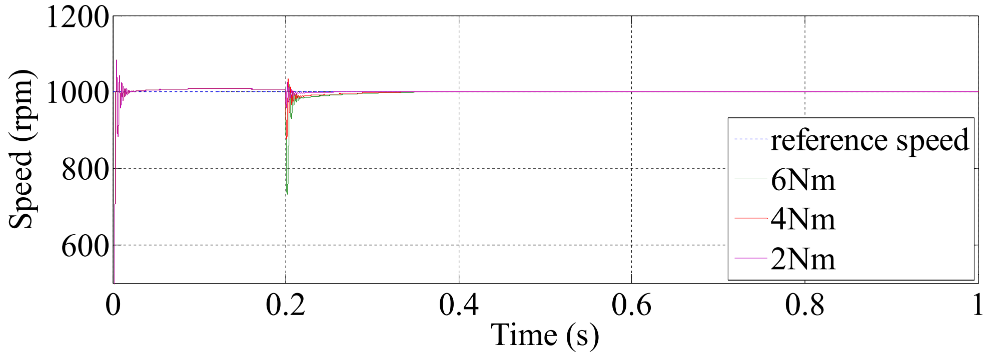

Figure 4.7: Speed (1000rpm) against the time

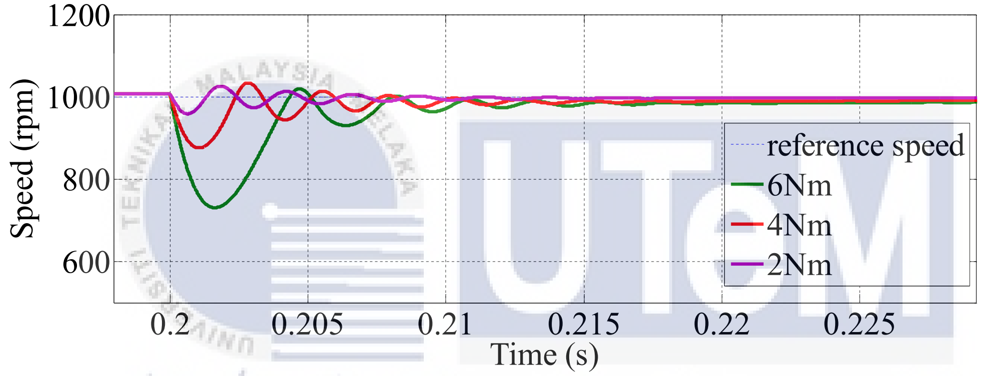

Figure 4.8: zoomed view of undershoot for speed response 1000rpm

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Figure 4.8 shows the speed response respect to the variance of input torques. The 1000rpm of PMSM was simulated with 6Nm, 4Nm and 2Nm of torque. From Figure 4.8, the speed dropped of 1000rpm are 270rpm, 123 and 40rpm with applied torque at 6Nm, 4Nm and 2Nm respectively.

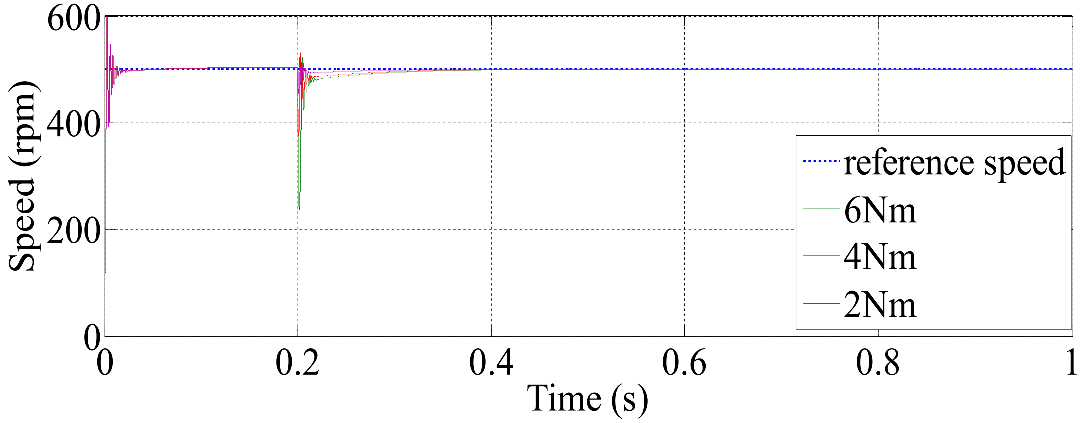

Figure 4.9: Speed (500rpm) against the time

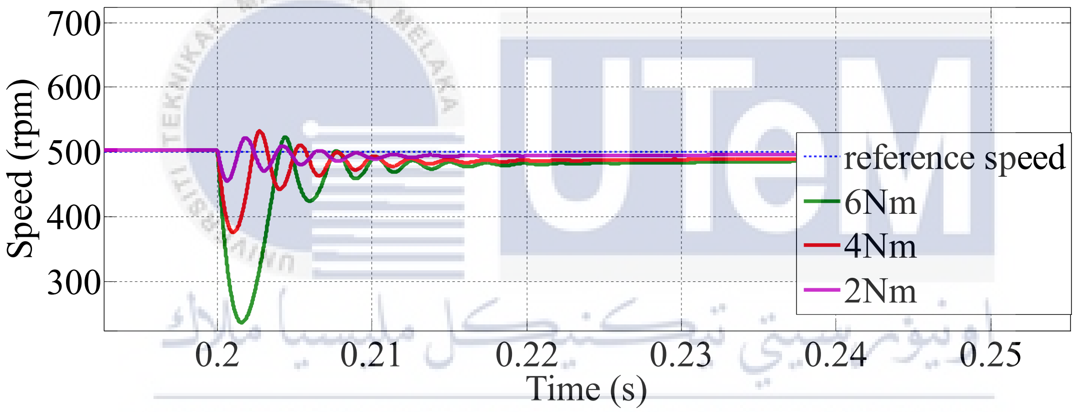

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Figure 4.10: zoomed view of undershoot for speed response 500rpm

Figure 4.10 shows the speed response respect to the variance of input torques. The 500rpm of PMSM was simulated with 6Nm, 4Nm and 2Nm of torque. From Figure 4.10, the speed dropped of 500rpm are 263rpm, 124 and 45rpm with applied torque at 6Nm, 4Nm and 2Nm respectively.

4.1.4 Discussion of Load Distubance for standard PMSM Drives

This subchapter explains the relationship of load disturbance respect to speed variance for standard PMSM drives using position sensor. Figure 4.16 below shows the speed dropped versus load variation for standard PMSM drives. From the Table 4.4 below, shows the data collected of speed dropped respect to torque. For torque at 6Nm, the speed dropped at 2000rpm, 1000rpm and 500rpm are 280rpm, 270rpm and 264rpm respectively. For torque at 4Nm, the speed dropped at 2000rpm,1000rpm and 500rpm are 120rpm,123rpm and 124rpm respectively. For the torque at 2Nm, the speed dropped at 2000rpm,1000rpm and 500rpm are 27rpm, 40rpm and 45rpm. From the above statement, it shows the standard PMSM drives have a stable performance because of the speed dropped it decrease evenly respect to all speed range. This can be concluded the speed dropped is increasing as the torque applied is increasing.

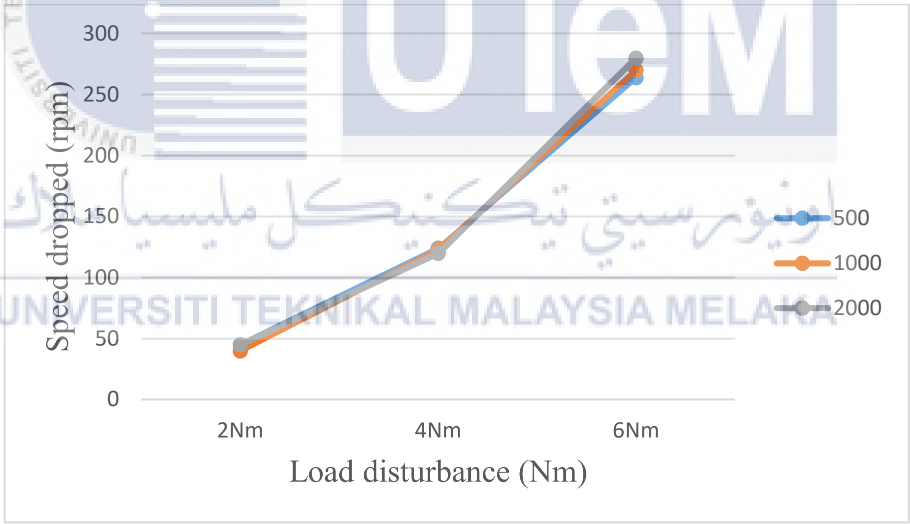

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Figure 4.11: Speed dropped versus load disturbance for standard PMSM Drives with sensor

Table 4.4: Speed dropped and load variation for standard PMSM Drives with sensor

	2000rpm	1000rpm	500rpm
2Nm	27	40	45
4Nm	120	123	124
6Nm	280	270	264

4.2 Sensorless PMSM Drives using MRAC based on Power Reactive Equation

This subchapter discussed the speed variation of sensorless PMSM Drives using MRAC based on Power Reactive Equation. The speed reference used are 2000rpm, 1000rpm and 800rpm with no-load condition.

4.2.1 Speed Variation of Sensorless PMSM Drives

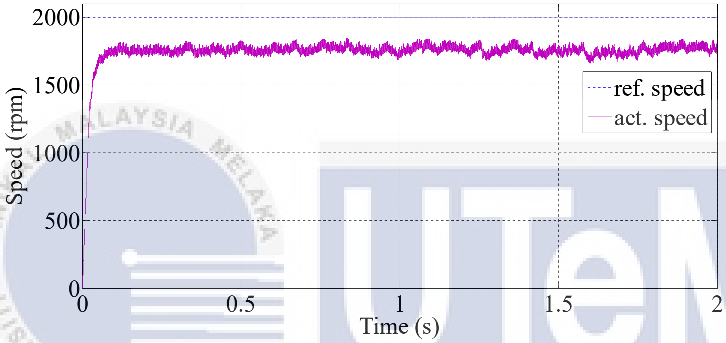

Figure 4.12: Speed response of sensorless PMSM at 2000rpm

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Figure 4.12 shows the speed response of sensorless PMSM at 2000rpm. The actual speed is around 1750rpm. It shows that this sensorless technique did not achieve the speed reference. The steady state error is about 250rpm.

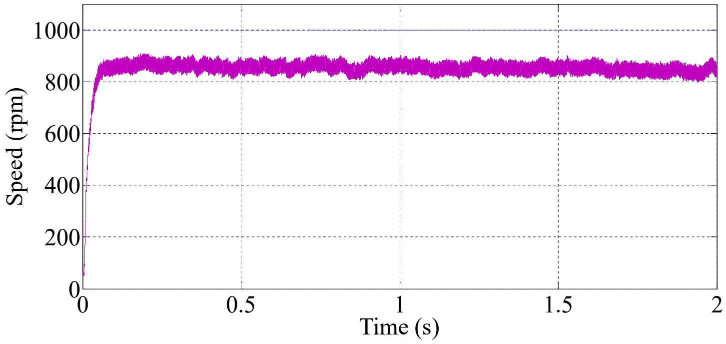

Figure 4.13: Speed response of sensorless PMSM at 1000rpm

Figure 4.13 shows the speed response of sensorless PMSM at 1000rpm. The actual speed is around 850rpm. The steady state error is 250rpm.

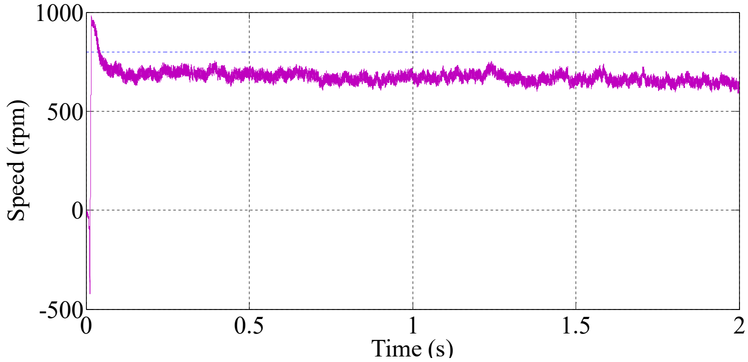

Figure 4.14: Speed response of sensorless PMSM at 800rpm

Figure 4.14 shows the speed response of sensorless PMSM at 800rpm. During start-up it shows the overshoot is at 960rpm then dropped at 700rpm.

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4.2.2 Discussion of Speed Variance for Sensorless PMSM Drives

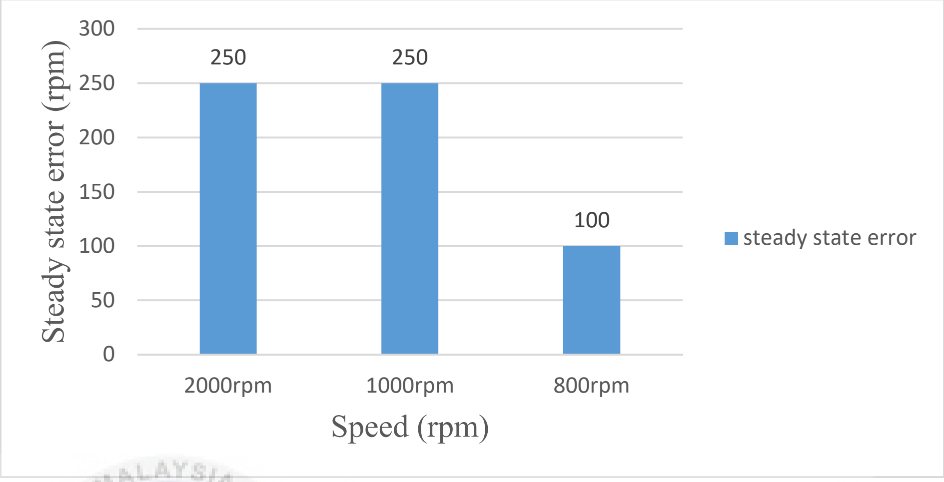

Figure 4.15: The steady state error against time

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Figure 4.15 shows the overall steady state error for speed reference 2000rpm,1000rpm and 800rpm is 250rpm, 250rpm and 100rpm respectively. From the Figure 4.15, it shows that for 2000rpm and 1000have have a same amount of steady state error. But, for 800rpm speed reference it has the least steady state error compared to 2000rpm and 1000rpm. This value of steady state error has occurred even no load has applied. This shows the sensorless control of PMSM Drives have lack in achieving the desired speed. Because of it can’t reach the satisfied desired speed, this drives need a lot of improvement and not qualified to test with load disturbance.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

A detailed Simulink model for PMSM drives based on MRAC Power Reactive Model has being developed in order to estimate the rotor speed and position without using the mechanical sensor. MATLAB/Simulink has been chosen as a simulation tools compared to the others because of its easily incorporated with mathematical equation in the presence of numerous tool block and and very reliable software. The literature review discusses the types of sensorless control of PMSM drives being used by other researchers. It is also included the comparison between each method in estimating the rotor position. The methodology also covers the steps of this project in order to achieve the objectives. The result of MRAC Power Reactive Model was compared and analyzed with standard PMSM drives to achieve the best result. A speed controller and current controller has been tuned successfully for closed loop operation for standard PMSM drives to run at desired speed with various load disturbance. On the other hand, the speed controller and current controller had some difficulties in tuning for sensorless PMSM drives using MRAC based on Power Reactive Equation. This cause the drive hardly to response according to given reference speed.

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5.2 Future works

For the recommendation, this project can be upgraded to use signal injection method for sensorless drives. This method is able to tackle the initial condition issues that occur when using fundamental excitation based. This is because signal injection method is more practical to use when deal with low speed response. High frequency voltage is injected on the top of the fundamental systems meanwhile signal processing is employed to extract rotor position. Furthermore, this project can be improved by using another sensorless technique that more robust such as artificial intelligent technique or have an advanced adaptive technique such as self-tuning control or sliding mode observer. Lastly, for the better understanding this project can be implemented in hardware module.

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