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FINAL YEAR PROJECT REPORT II

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


**Name : MUHAMMAD AMIRUL ASYRAF BIN MAHMUDDIN**

**Matric No . : B011410091**

**Supervisor : DR JURIFA BT. MAT LAZI**

**Course : BACHELOR OF ELCTRICAL ENGINEERING (POWER INDUSTRY)**

“I hereby declare that I have read through this report entitle “Sensorless Control of PMSM Drives using Voltage Model Based on Power Reactive Equation” and found that it has complied the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Industrial Power)”

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| Supervisor’s Name | : ………………………………….. |
| Date | : ………………………………….. |

**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)**

**Faculty of Electrical Engineering**
**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2017**

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.

## 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 mencadangankan 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 |

**Symbols**

| | |
|---|---|
| $\alpha\beta$ | Stationary stator reference frame axes |
| $\beta$ | viscous friction coefficient |
| $\zeta$ | damping ratio |
| $\varepsilon$ | 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 |
| $\omega m$ | reference rotor speed |
| Ψpm | permanent magnet flux |
| ψd,ψq | d-q axis stator flux |
| $Vdc$ | DC link voltage |
| θ | angular position |

**Subscripts**

| | |
|---|---|
| a,b,c | Stator a,b,c phases |

# 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.

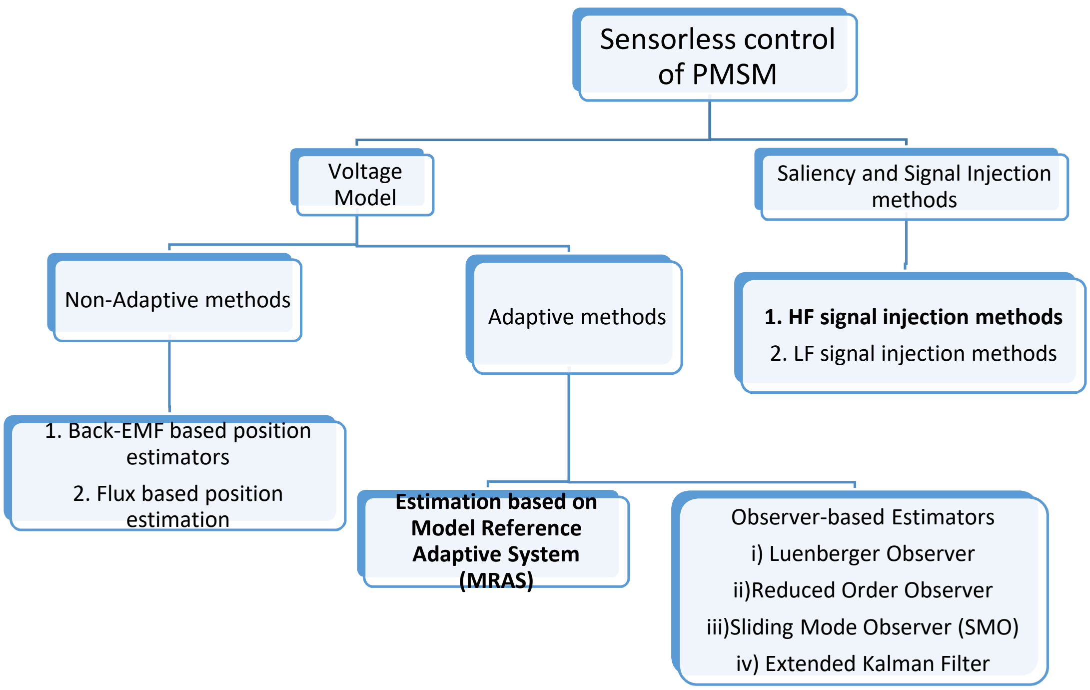


Figure 1.1: Common sensorless control technique for PMSM[4]

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.

## 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.

## 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.

# 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.

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.

### 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

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