SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR USING ARTIFICIAL NEURAL NETWORK

NOORADZIANIE BINTI MUHAMMAD ZIN

A thesis submitted in fulfillment of the requirement for the award of the Degree of Master

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2016
Special dedicated to my mother Siti Rukiah bt Shafie, my father Muhammad Zin bin Boharom, my husband Mohd Firdaus bin Ahmad and my daughter Nada Dhia Azra

Bt Mohd Firdaus thank you so much for the support and attention to me.
ACKNOWLEDGEMENT

First of all, Alhamdullilah, praise to Allah for His Blessings I have finished writing this dissertation for Master of Electrical Engineering. I express my sincere appreciation to my supervisor, Dr Wahyu Mulyo Utomo for his encouragement, guidance, advices and critics. Without his continuous support and interest, this research could not be finished.

I would like to gratitude faculty of electrical and electronic engineering (FKEE) University Tun Hussein Onn Malaysia for any valuable supports during conducting this project and in preparing this report.

My appreciation also goes to my family especially my husband and my parents for their biggest support and involvement in every aspect. Last but not least, my appreciation goes to my fellow friends and everyone involved directly or indirectly in order to finish this study and compilation of this dissertation.
The performance analysis on the principle of operation, design considerations and control algorithm of the field oriented control (FOC) for a permanent magnet synchronous motor (PMSM) drive system in close loop operation are presented in this study. To improve the speed tracking and load disturbance performance of PMSM drive system, an online learning backpropagation algorithm Artificial Neural Network (ANN) speed controller by feedforward architecture is proposed. The proposed controller was compared to offline learning ANN in order to show the performance differentiation between both online and offline learning methods. The ANN for both speed controllers are defined as 1-3-1 network structure. Using the output of the ANN speed controller, the quadrature axis reference current value can be obtained. While, for the direct axis reference current value is set to zero. Then, the value of direct and quadrature axis current are produced by FOC in order to decouple the torque and flux. These values differentiations are become the input of torque and flux controller that used proportional integral (PI) controller. The capability of the proposed ANN has been verified in simulation model by using Simulink/Matlab and experimentally by using Digital Signal Processor Controller. From the simulation and experimental results show that the proposed online learning ANN speed controller adaptively tackles the load variations and enables the drive system to follow the reference speed quickly compared to offline learning ANN speed controller. It can conclude that, the proposed online learning ANN speed controller has better performance rather than offline learning ANN speed controller in term of settling time, speed error after steady at one point and momentary under speed.
ABSTRAK

# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE</td>
<td>i</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF SYMBOLS AND ABBREVIATIONS</td>
<td>xvii</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xx</td>
</tr>
</tbody>
</table>

## CHAPTER 1 INTRODUCTION

1.1 Introduction 1

1.2 Research background 1

1.3 Problem statement 3

1.4 Research objectives 5

1.5 Scope and delimitation of the research 5

1.6 Thesis outline 6
CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

2.2 Classification of electric motors

2.3 Permanent magnet synchronous motor (PMSM)

2.4 PMSM control strategy

2.5 Field oriented control (FOC)

2.6 Review of existing previous work

2.6.1 Sinusoidal type of PMSM selection

2.6.2 Variable speed control motor selection

2.6.3 FOC of PMSM drive system with conventional speed controller

2.6.4 FOC of PMSM drive system with artificial intelligent speed controller

2.7 Gap of study

CHAPTER 3 METHODOLOGY

3.1 Introduction

3.2 Research flow chart

3.3 Control strategy of the FOC for PMSM drive system

3.3.1 Flux and torque controller

3.3.2 Determination of reference direct-axis current, Id*

3.3.3 Determination of PMSM rotor position, θ
3.3.4 Park and clarke transformation

3.4 Proposed ANN speed controller structure

3.4.1 Online and offline learning ANN

3.5 Load testing calculation

CHAPTER 4 RESULT AND ANALYSIS

4.1 Introduction

4.2 Overview of systems developments

4.3 Execution of proposed design in simulink-Matlab

4.3.1 Space vector pulse width modulation block

4.3.2 Inverter in simulink block

4.3.3 Field oriented control (FOC)

4.4 Simulation results and discussion

4.4.1 Constant speed simulation testing

4.4.2 Speed response simulation testing

4.4.3 Load disturbance constant speed simulation testing

4.4.4 Summarization of simulation results

4.5 Experimental evaluation

4.5.1 The real-time interface integration with TMS320F2800 DSP controller

4.5.1.1 Speed detection design

4.5.1.2 Current detection design
4.6 Operation of experimental PMSM drive system

4.7 Experimental results and discussion
4.7.1 Constant speed experimental testing
4.7.2 Speed response experimental testing
4.7.3 Load disturbance constant speed experimental testing
4.7.4 Summarization of experimental results

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 Conclusion
5.2 Future work

LIST OF PUBLICATIONS

REFERENCES

APPENDIX

VITA
LIST OF TABLES

2.1 Gap of study for the ANN based field oriented control of PMSM drive according to the several recent works 26
4.1 Constant speed simulation testing results summarize 56
4.2 Speed response simulation testing results summarize 57
4.3 Load disturbance constant speed simulation testing results summarize 57
4.4 Constant speed experimental testing results summarize 73
4.5 Speed response experimental testing results summarize 73
4.6 Load disturbance constant speed experimental testing results summarize 74
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Classification of electric motors</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Classification of permanent magnet machine</td>
<td>10</td>
</tr>
<tr>
<td>2.3</td>
<td>Control scheme for PMSM</td>
<td>12</td>
</tr>
<tr>
<td>2.4</td>
<td>Block diagram of FOC control of PMSM</td>
<td>17</td>
</tr>
<tr>
<td>2.5</td>
<td>Identification of PMSM using ANN</td>
<td>20</td>
</tr>
<tr>
<td>2.6</td>
<td>Block diagram of the proposed ANN based IPMSM drive</td>
<td>21</td>
</tr>
<tr>
<td>2.7</td>
<td>Control structure of NN-MPDSC</td>
<td>22</td>
</tr>
<tr>
<td>2.8</td>
<td>Block diagram of speed control system of PMSM drive</td>
<td>23</td>
</tr>
<tr>
<td>3.1</td>
<td>Research flow chart</td>
<td>29</td>
</tr>
<tr>
<td>3.2</td>
<td>PMSM drive system with proposed ANN controller</td>
<td>30</td>
</tr>
<tr>
<td>3.3</td>
<td>Block diagram of PI for flux and torque controller</td>
<td>31</td>
</tr>
<tr>
<td>3.4</td>
<td>Block diagram of ANN speed controller for FOC PMSM</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>drive</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Offline learning algorithm</td>
<td>38</td>
</tr>
<tr>
<td>3.6</td>
<td>Online learning algorithm</td>
<td>39</td>
</tr>
<tr>
<td>4.1</td>
<td>PMSM drive system general block diagram for simulation part</td>
<td>42</td>
</tr>
</tbody>
</table>
4.2 General diagram of PMSM drive system for simulation and experimental part

4.3 Simulation circuit of ANN speed controller in Simulink/Matlab

4.4 SVPWM subsystem block

4.5 Inverter calculation

4.6 Clarke transformation calculations

4.7 Park transformation calculations

4.8 Inverse park transformation calculations

4.9 The speed and current response for the speed of 500rpm with 0.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN

4.10 The speed and current response for the speed of 700rpm with 0.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN

4.11 The speed and current response for the speed of 1000rpm with 0.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN

4.12 The speed and current response for the speed of 500rpm with 1.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN

4.13 The speed and current response for the speed of 700rpm with 1.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN

4.14 The speed and current response for the speed of 1000rpm with 1.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN
4.15 The speed and current response for a step response during 0.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN

4.16 The speed and current response for a step response during 1.2Nm load torque applied: (a-b) Online ANN; (c-d) Offline ANN

4.17 Load regulation performance response for a constant speed of 500rpm (a-b) Online ANN, (c-d) Offline ANN

4.18 Load regulation performance response for a constant speed of 700rpm (a-b) Online ANN, (c-d) Offline ANN

4.19 Load regulation performance response for a constant speed of 1000rpm (a-b) Online ANN, (c-d) Offline ANN

4.20 Hardware implementation with C2000 DSP digital controller

4.21 Real-Time interface of the proposed ANN speed controller

4.22 Estimation of speed encoder pulses counting

4.23 Real pulse detected from encoder during experimental

4.24 Experimental setup for proposed PMSM drive system with ANN

4.25 Experimental step response for a reference speed 500rpm at a load of 0.2Nm: (a) Online ANN speed response; (b) Online ANN current response; (c) Offline ANN speed response; (d) Offline ANN current response

4.26 Experimental step response for a reference speed 700rpm at a load of 0.2Nm: (a) Online ANN speed response; (b) Online ANN current response
4.27 Experimental step response for a reference speed 1000rpm at a load of 0.2Nm: (a) Online ANN speed response; (b) Online ANN current response; (c) Offline ANN speed response; (d) Offline ANN current response

4.28 Experimental step response for a reference speed 500rpm at a load of 1.2Nm: (a) Online ANN speed response; (b) Online ANN current response; (c) Offline ANN speed response; (d) Offline ANN current response

4.29 Experimental step response for a reference speed 700rpm at a load of 1.2Nm: (a) Online ANN speed response; (b) Online ANN current response; (c) Offline ANN speed response; (d) Offline ANN current response

4.30 Experimental step response for a reference speed 1000rpm at a load of 1.2Nm: (a) Online ANN speed response; (b) Online ANN current response; (c) Offline ANN speed response; (d) Offline ANN current response

4.31 Experimental results due to periodical step command under 0.2Nm load: (a) Online ANN speed variation response; (b) Online ANN current response; (c) Offline ANN speed variation response; (d) Offline ANN current response

4.32 Experimental results due to periodical step command under 1.2Nm load: (a) Online ANN speed variation response; (b) Online ANN current response; (c) Offline ANN speed variation response; (d) Offline ANN current response

4.33 System response due to load torque rejection at 500rpm: (a) Online ANN speed response; (b) Online ANN current response; (c) Offline ANN speed response; (d) Offline ANN current response
4.34 System response due to load torque rejection at 700rpm: (a) Online ANN speed response; (b) Online ANN current response; (c) Offline ANN speed response; (d) Offline ANN current response

4.35 System response due to load torque rejection at 1000rpm: (a) Online ANN speed response; (b) Online ANN current response (c) Offline ANN speed response; (d) Offline ANN current response
# LIST OF SYMBOLS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Alpha</td>
</tr>
<tr>
<td>$a,b,c$</td>
<td>Three-phase Stator Current</td>
</tr>
<tr>
<td>$A$</td>
<td>Ampere</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Beta</td>
</tr>
<tr>
<td>$d$</td>
<td>Direct</td>
</tr>
<tr>
<td>$h_v$</td>
<td>Sampling Period</td>
</tr>
<tr>
<td>$L_d$</td>
<td>d-Axis Inductance</td>
</tr>
<tr>
<td>$L_q$</td>
<td>q-Axis Inductance</td>
</tr>
<tr>
<td>$N_m$</td>
<td>Newton Meter</td>
</tr>
<tr>
<td>$N_{enc}$</td>
<td>Encoder Pulse per Revolution</td>
</tr>
<tr>
<td>$N_p$</td>
<td>Encoder Pulse</td>
</tr>
<tr>
<td>$q$</td>
<td>Quadrature</td>
</tr>
<tr>
<td>rpm</td>
<td>Rotation Per Minute</td>
</tr>
<tr>
<td>$V$</td>
<td>Voltage</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Theta/ Angle/ Rotor Position</td>
</tr>
<tr>
<td>kW</td>
<td>Kilo Watt</td>
</tr>
<tr>
<td>$V/f$</td>
<td>Voltage/Frequency</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog Digital Converter</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>BDCM</td>
<td>Brushless DC Motor</td>
</tr>
<tr>
<td>DBP</td>
<td>Dynamic Back Propagation</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DRNN</td>
<td>Diagonal Recurrent Neural Network</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>DTC</td>
<td>Direct Torque Control</td>
</tr>
<tr>
<td>FL</td>
<td>Fuzzy Logic</td>
</tr>
<tr>
<td>FOC</td>
<td>Field Oriented Control</td>
</tr>
<tr>
<td>IM</td>
<td>Induction Motor</td>
</tr>
<tr>
<td>IO</td>
<td>Input Output</td>
</tr>
<tr>
<td>IPMSM</td>
<td>Interior Permanent Magnet Synchronous Motor</td>
</tr>
<tr>
<td>MP-DSC</td>
<td>Model Predictive Direct Speed Control</td>
</tr>
<tr>
<td>NN</td>
<td>Neural Network</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent Magnet</td>
</tr>
<tr>
<td>PMAC</td>
<td>Permanent Magnet Alternating Current</td>
</tr>
<tr>
<td>PMDC</td>
<td>Permanent Magnet Direct Current</td>
</tr>
<tr>
<td>PMSM</td>
<td>Permanent Magnet Synchronous Motor</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>RNN</td>
<td>Recurrent Neural Network</td>
</tr>
<tr>
<td>RROP</td>
<td>Resilient Back Propagation</td>
</tr>
<tr>
<td>SPMSM</td>
<td>Surface Permanent Magnet Synchronous Motor</td>
</tr>
<tr>
<td>SVPWM</td>
<td>Space Vector Pulse Width Modulation</td>
</tr>
<tr>
<td>SW</td>
<td>Sliding Window</td>
</tr>
<tr>
<td>VC</td>
<td>Vector Control</td>
</tr>
<tr>
<td>2DOFC I-PD</td>
<td>Two-Degree-Of-Freedom Integral Plus Proportional</td>
</tr>
<tr>
<td>Appendix</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>A</td>
<td>Dynamic modelling of permanent magnet synchronous motor</td>
</tr>
<tr>
<td>B</td>
<td>Space vector pulse width modulation module</td>
</tr>
<tr>
<td>C</td>
<td>Ziegler Nichols $K_p$ and $K_i$ tuning method</td>
</tr>
<tr>
<td>D</td>
<td>FOC block coding</td>
</tr>
<tr>
<td>E</td>
<td>Pulse counting block coding</td>
</tr>
<tr>
<td>F</td>
<td>ANN block coding</td>
</tr>
<tr>
<td>G</td>
<td>Determine initial weights and biases by using NF Tool</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Introduction

In this chapter, the introduction of the research will be explained in detail in which consists of the research background towards the focusing of the research study, problem statement, research aim, research objective, research scopes and research outline.

1.2 Research background

Recent developments in power semiconductor technology, digital electronics, magnetic materials, and control algorithms have enabled modern ac motor drives to satisfy challenging high-efficiency and high performance requirements in the industrial sector. Among AC drives, permanent magnet synchronous motors (PMSM) are widely used in low and mid power applications and also can compete with an induction machine such as computer peripheral equipment, robotics, adjustable speed drives and electric vehicles. This is because PMSM has a characteristic of high power density, easy maintenances, compact size, high speed range and high efficiency, which has been widespread application in the various electric drives applications [1][2][3][4][5].

Since 1988, Pillay, P and Krishnan, R. has been presented about PM motor drives and classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives [6]. The PMSM has a
sinusoidal back emf and fed with sinusoidal stator currents while the BDCM has a trapezoidal back emf and fed with direct current. The PMSM is very similar to the wound rotor synchronous machine except that the PMSM is used for servo applications tends not to have any damper windings and excitation is provided by a permanent magnet instead of a field winding. The PM motor family incorporates two designs: internal rotor and external rotor. Both designs are industrially rated and adopted in critical applications such as elevator winches and wind power generators.

In order to achieve high performance, the drive system need to quickly achieve the command speed and maintain the operating point with maximum accuracy and minimal perturbation despite the occurrence of sudden and unknown disturbances. Conventionally, proportional-integral (PI) and proportional-integral-derivative (PID) speed controllers have been utilized to meet these control challenges since it slightly simple to implement [7][8]. Other than that, by using Proportional-Integral-Derivatives (PID) controller exact dq axis reactance parameters can be obtained and zero steady state error can be achieved [9].

Even though PID being the most simple and the widely deployed controller in the industrial drives, it is not quite amenable to the solution for high performance drives as these drives are subjected to the parametric uncertainty, unmodeled dynamics and variable load condition during operation [10]. So, for this case an artificial neural network (ANN) is used in order to expand the efficiency and adaptive capabilities of conventional PID controller. The ANN is best suited for solving the problems that are nonlinear in nature. ANN can use parallel processing methods to solve some real-world problems where it is difficult to define a conventional algorithms. The ability of ANN to learn large classes of nonlinear functions is well known [11][12]. Other than that, the ANN is a processing system consisting of a large number of simple highly interconnected processing elements in an architecture inspired by the structure of the cerebral cortex of the brain [13]. It can be trained to emulate the unknown nonlinear plant dynamics by presenting a suitable set of input/output patterns generated by the plant. Once system dynamics has been identified by using an ANN, many conventional control techniques can be applied to achieve the desired objective. There are two types of learning in ANN which are supervised and unsupervised learning. In supervised learning, the difference between the actual output and the desired output are minimised during the training process,
while in unsupervised learning, the desired output is unknown, and learning is based on the correlation of input values [14]. Furthermore, an ANN-based speed controller is computationally intensive and can be chosen either online or offline learning with the help of training algorithms and a predefined dataset [15].

Field Oriented Control (FOC) technique has been chosen for this system to achieve the objective and moreover the PM synchronous motors can be used in Vector Control (VC) or so called (FOC) applications [3]. FOC of PMSM is widely used in industries and household applications. FOC scheme not only decouples the torque and flux which makes faster response but also makes control task easy [16]. In FOC, motor stator currents and voltages are manipulated in the direct-quadrature (d-q) reference frame of the rotor. By using SVPWM, it will help the dynamic response of the system faster.

For this project, a model of online learning ANN closed-loop PMSM control system that is controlled by SVPWM are developed for speed performance in the FOC PMSM drive. The effectiveness of the proposed method is verified by developing simulation models in MATLAB-Simulink and experimental by comparing with the offline learning ANN control system.

### 1.3 Problem statement

In recent years, PMSM are increasing applied in several areas such as traction, automobiles, robotics and aerospace technology. Accurate digital simulation tools are necessary to evaluate their field performance particularly when they are driven with solid-state drives connected to larger electrical networks [17]. This type of motor is most applicable where the high speed performance is needed. With elimination of commutator, PMSM is become more reliable than a DC motor and become more efficient than an AC induction because the production of the rotor flux is from permanent magnet [18]. Unfortunately the operation of PMSM is much more complicated compared to DC motor and lack of precision control as the flux and torque component of its input current are coupled.

However, the complicated coupled nonlinear dynamic performance of PMSM can be significantly improved by using FOC theory where torque and flux can be controlled separately. In addition, the variable to be controlled (speed, position, or
torque) is the main difficulty lies in the necessity of controlling the torque which implies the control of the stator current [19]. To do that, the FOC is one of the vector based method that aims to control the torque and rotor flux of the PMSM effectively. Under perfect field orientation and with constant flux operation, a simple linear relation can characterize the torque production in the motor when the magnetic circuit is linear. Even so, the control performance of PMSM drive is still influenced by uncertainties, which usually are composed of unpredictable plant parameter variations, external load disturbances and nonlinear dynamics of the plant. The PMSM owns high thrust density to ensure high level of dynamic performance, but it is more sensitive to various disturbances than rotational actuators [20]. So, one of the areas of interest is the design of controllers for these motor drives in order to overcome this problem.

Conventionally, in industrial application, servo drive of PMSM generally uses the traditional proportional integral (PI) controller with fixed parameters as the control system using PI controller presents simplicity and feasibility to a certain extent, it is not robust enough to accommodate the uncertainties [18][20][21][22]. However, numerous methods have been proposed to replace PI control schemes. For this project, an online learning Artificial Neural Network (ANN) has been proposed to improve speed tracking and load disturbance performance of the PMSM. ANN offers the advantage of performance improvement through learning using parallel and distributed processing. These networks are implemented by using massive connections among processing units and are attractive for wide applications in system identification and motion controls [21]. Recent development in the NN technology has made it possible to train an ANN to represent a variety of complicated nonlinear systems. Online NN is chosen according to the fact that even offline model can handle large data as computation time that not critical to their structure, it only robust to small variation, but fail to adapt to larger changes in the system. While, the online model adapts to variation quickly in the non-linear behaviour of the system [23].

By these reasons, this project implement an online ANN for identification and control of FOC PMSM drive system based SVPWM technique. The ability of the proposed controller is being test with different load torque and variety of speed target even in the presence of load disturbance by simulation and experimental.
1.4 Research objectives

The purpose of this study is to describe a comprehensive analysis on the principle of operation, design considerations and control algorithms of a PMSM drive. This project is focusing on speed controller of a FOC for PMSM drives system. An investigation on performance and for the motor control strategy will be carried out. This project will introduce an online learning ANN to improve the controller of the motor. The objectives of the project are:

i. To develop simulation model and prototype of the FOC PMSM drive system.

ii. To design an offline and online learning feedforward ANN speed controller for PMSM drive system.

iii. To verify proposed FOC of PMSM drive system in simulation and experimental set up.

1.5 Scope of the research

This project was conducted at the following scope:

i. Simulation model development
   - The Matlab Simulink is used in order to model and simulate the FOC PMSM drive system.

ii. Controller program development
   - The backpropagation algorithm will be implemented in the ANN design.

iii. Hardware development
   - The TMS320F28335 Picolo board is used as a controller.

iv. The motor specification for hardware is given as below:
   - Frequency, $f$: 50Hz
   - Pole, $p$: 4
   - Stator Resistance, $R_s$: 2.875Ω
   - Stator-Rotor Self Inductances, $L_d$, $L_q$: 0.0085H
   - Moment of Inertia, $J$: 0.0008kgm$^2$
   - PM Flux Linkage, $\lambda_{PM}$: 0.175Wb
   - Friction Coefficient, $K_f$: 0.00038818
1.6 Thesis outline

This thesis explains about design, comparison and performance of proposed online ANN for PMSM drive system. This thesis is divided into five chapters and the summary of each chapter is given below.

(a) Chapter 1: Introduction
The first chapter gives some introduction about the background of the research. The problems of previous work are highlighted and the research objectives are also discussed in this chapter.

(b) Chapter 2: Literature Review
The second chapter explained the electric motor classification. In addition, advantages AC over DC motor and its control method also discussed in this chapter. The review of previous and currently research in FOC of PMSM drive system are presented.

(c) Chapter 3: Research Methodology
This chapter describes the project implementation of this project. The explanation of the proposed design ANN speed controller in FOC of PMSM is discussed. The control algorithm of the ANN is explained in details.

(d) Chapter 4: Results and Analysis
This chapter describes the performances of proposed online ANN speed controller of PMSM drive system for both simulation and hardware implementation in this project. The proposed design is simulated by using Matlab Simulink Software, while the experiment is controlled through the C2000 DSP controllers, TMS320C2800 controller board. The performance obtained from simulation is verified by the experiment result.

(e) Chapter 5: Conclusion and Future Work
The final chapter describes and concludes the summary of the project. The objectives in this project are successfully achieved. Also the suggestions of future work are described in this chapter.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will explain the permanent magnet synchronous motor fundamentals knowledge. The in depth studies of the convenient control method for motor drive system together with the FOC and proposed ANN method will be discussed as well in this chapter. Furthermore, some previous work that related to this project also will be discussed in order to expose and giving the overview of the concept and the idea of the whole project.

2.2 Classification of electric motors

Among all of the existing motors on the market, there are three ‘classical’ motors which are the Direct Current with commutators (wound field) and two Alternative Current motors the synchronous and the asynchronous motors. These motors, when properly controlled, produce constant instantaneous torque (very little torque ripple) and operate from pure DC or AC sinewave supplies. Figure 2.1 shows the classification of electric motors.

An AC electric motor commonly ran by an AC variable frequency drive and operates by applying alternating current (AC) power to the electric motor. An AC electric motor consists of several parts but the main parts are the stator and rotor. The AC electric motor’s stator has coils that are supplied with the alternating current and produces a rotating magnetic field. The AC electric motor’s rotor rotates inside the
electric motor's coils and is attached to an output shaft that produces torque by the rotating magnetic field. There are two different types of AC electric motors and each of them uses a different type of rotor. The first type of AC motor is called an induction motor (also known as an asynchronous motor).

An induction motor uses a magnetic field on the rotor of an induction motor that's created by an induced current. The other type of AC motor is called a synchronous motor and rotates precisely at the supply frequency or on a sub-multiple of the supply frequency.

A synchronous motor is able to operate with precision supply frequency because it doesn't reply on induction. The magnetic field on a synchronous motor is generated by current delivered through slip rings or a permanent magnet. Synchronous motors run faster than induction motors because the speed is reduced by the slip of the asynchronous motor.

![Diagram of electric motors classification](image)

Figure 2.1 Classification of electric motors

While, DC electric motors are powered from direct current (DC) supply and mechanically commutated machines. DC electric motors have a voltage induced rotating armature winding, and a non-rotating armature field frame winding that is a static field, or permanent magnet. DC electric motors use different motor connections of the field and armature winding to produce different speed and torque regulation.
DC electric motor speed can be controlled within the winding by changing the voltage applied to the DC motor armature, or by adjusting the field frame current. DC motors are usually seen in applications where the motor speed needs to be externally controlled.

AC motors work best in applications where power performance is sought for extended periods of time. All DC motors are single phase, but AC motors can be single phase or three phase. AC and DC motors use the same principle of using an armature winding and magnetic field except with DC motors, the armature rotates while the magnetic field doesn’t rotate. In AC motors the armature does not rotate and the magnetic field continuously rotates. In some applications today, DC electric motors are replaced by combining an AC electric motor with an electronic speed controller. DC electric motors are replaced with an AC electric motor and an electronic speed controller because it is a more economical and less expensive solution. Furthermore, DC electric motors have many moving parts that are expensive to replace, and DC electric motor repair is usually more expensive than using a new AC electric motor with an electronic controller. Other than that, the AC servo drives, including PMSM have been widely used in robotics, computer-numerically-controlled machine tools, elevators and many other applications in the area of mechatronics nowadays. So, for this project PMSM has been choosing in order to investigate their performance due to higher efficiency owing to the absence of rotor losses and lower no-load current below the rated speed compared to induction motor [24].

2.3 Permanent magnet synchronous motor (PMSM)

Permanent Magnet (PM) electric machines are classified into two groups as depicted in Figure 2.2. The Permanent Magnet Direct Current (PMDC) machines are similar with the Direct Current (DC) commutator machines but the field winding is replaced by the PM while in case of Permanent Magnet Alternating Current (PMAC) the field is generated by the PM placed on the rotor and the sliprings, brushes and commutator does not exist in this machine type. By these reasons, the PMAC machine is simpler and more attractive to use instead of PMDC [77].
The trapezoidal PMAC machines also called Brushless DC motors (BLDC) has a trapezoidal-shaped back EMF and develop trapezoidal back EMF waveforms with following characteristics:

- Rectangular current waveform
- Rectangular distribution of magnet flux in the air gap
- Concentrated stator windings

While the sinusoidal PMAC machines, called PMSM has a sinusoidal shaped back EMF and develop sinusoidal back EMF waveform with following characteristics:

- Sinusoidal current waveform
- Sinusoidal distribution of magnet flux in the air gap
- Sinusoidal distribution of stator conductors

Based on the rotor configuration the PMSM broadly can classify as:
Surface mounted magnet type (SPMSM)

For this case, the magnets are mounted on the surface of the rotor. The magnets can be regarded as air because the permeability of the magnets is close to unity and the saliency is not present due to same width of the magnets. Therefore the inductance expresses in the quadrature coordinate are equal ($L_d = L_q$). In the case of SPMSM the saliency is not present, making this machine easier to design.

Interior Magnet type (IPMSM)

While for this type of motor, the magnets are place inside the rotor. In this configuration saliency is available and the air gap of d-axis is greater than q-axis air gap and resulting that the q axis inductance has different value than the d axis inductance. There is inductance variation for this type of rotor because the permanent magnet part is equivalent to air in the magnetic circuit calculation. These motors are considered to have saliency with q axis inductance greater than the d axis inductance ($L_q > L_d$).

Further, among IPMSM and SMPMSM, SMPMSM is commonly used nowadays. This is because IPMSM have an even higher power density than SPMSM which represent the standard in industrial applications so far. This advantage can ascribed to strongly asymmetric reluctance in IPMSM, which make the modelling and control more complex.

PMSM uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. PMSM drive with a sinusoidal flux distribution [25]. Compared to induction servo motor, a PMSM have such advantages as higher efficiency owing to the absence of rotor losses and lower no load current below the rated speed. Moreover, its decouple control performance is much less sensitive to the parameter variations of the motor [26]. Recently, the PMSM has emerged as an alternative to the induction motor in various applications because of the high efficiency and the reduced size [26][27]. There are some advantages of PMSM as state below [28]:

- Torque to inertia ratio of PM machine is high
- High efficiency than Induction Motor
- PM already has the excitation in the form of rotor magnet
- PM have some output capacity with Induction Motor
- Smaller size than Induction Motor
- Light but power density is high
- Rotor losses in PM are negligible/ low rotor inertia
- The ratio of the copper and iron power losses is a key issue in determining the maximum efficiency

2.4 **PMSM control strategy**

During the past three decades, adjustable speed ac drive technology has gained a lot of momentum. The variable speed drive scenario is characterized by the cage induction motor, wound rotor synchronous motor and the new category of permanent magnet brushless synchronous and dc motors. The vector control technique was firstly proposed for induction motors, while it was applied to PMSM later [29]. The variable speed control method is shown in Figure 2.3.

![Control scheme for PMSM](image)

Figure 2.3 Control scheme for PMSM

V/f control is among the simplest control. The control is an open loop and does not use any feedback loop. The idea is to keep stator flux constant at rated value so that the motor develop rated torque/ampere ratio over its entire speed range.
However, when PMSM drives are used for applications like pumps and fans, where high dynamic performance is not a demand, a simple V/f control strategy can be used [30]. In addition, the V/f control does not provide very good performance as field oriented control (FOC) [27].

Direct torque control (DTC) has closed-loop control both of torque and stator flux, which was firstly proposed for IM [31]. At present, DTC has become a powerful and widely used control strategy of AC machines including of PMSM since 1997 [32]. The basic principle of DTC is to directly select stator voltage vectors according to the difference between the references of torque and stator flux linkage and their actual values [33]. The $dq$ axis vector decoupling of field oriented control (FOC) is replaced by two hysteresis controllers of DTC, which meets very well with the on-off operation of power transistors of inverter. However, the disadvantages of basic DTC is also obvious which are the torque and flux ripple, dilapidated performance during low speed and variable switching frequency of inverter [34].

The principle of field oriented control (FOC) was first proposed in the early 1970s for controlling induction motors. This method had been developed into a complete theory system within several years of efforts. Due to rapid progress in power electronics, the FOC has been used wider and wider in high performance AC drives in the latest twenty years [35]. In practice, FOC requires accurate knowledge of the motor parameter [36].

### 2.5 Field oriented control (FOC)

In order to achieve the desired performances of PMSMs as the behaviour of DC motors, direct control of stator currents is needed. Nevertheless, it is quite unattainable due to the strong coupling and nonlinear natures of the AC motors. Hence, to realize the decoupling of relevant variables, a particular algorithm must be introduced. So, this problem has been resolved by the vector control technology, often referred to as FOC [35]. The FOC of PMSM motor drive gives improved performance in terms of faster dynamic response and more efficient operation. The FOC or known as vector control method gives the performance characteristics similar to that of a DC machine which are considered desirable in certain applications [3]. The inexplicable dynamic behaviour of large current transients and
The resulting failure of inverters was a curse and barrier to the entry of inverter fed ac drives into the market. FOC is a control procedure for operating the motor that results in fast dynamic response and energy efficient operation at all speeds.

The fundamental weakness of sinusoidal commutation is that it attempts to control motor currents that are time variant in nature. This breaks down as speeds and frequencies go up due to the limited bandwidth of PI controllers. FOC solves this problem by controlling the current space vector directly in the $d-q$ reference frame of the rotor.

The goal of the FOC is to perform real-time control of torque variations demand, to control mechanical speed and to regulate phase currents in order to avoid current spikes during transient phases. To perform these controls, the electrical equations are projected from a 3 phase non-rotating frame into two co-ordinate rotating frame. In the ideal case, the current space vector is fixed in magnitude and direction (quadrature) with respect to the rotor, irrespective of rotation. Because the current space vector in the $d-q$ reference frame is static, the PI controllers operate on dc, rather than sinusoidal signals. This isolates the controllers from the time variant winding currents and voltages, and therefore eliminates the limitation of controller frequency response and phase shift on motor torque and speed. Using FOC, the quality of current control is largely unaffected by speed of rotation of the motor [37]. Other than that, the rotor flux in the $d$-axis can be controlled using $d$-axis stator current, $i_d = 0$ in FOC [38].

### 2.6 Review of existing previous work

In order to find good motor candidates for high performance applications for this project, some review has been made among PMAC machine. Next, in synchronous machine the original nonlinear structures are coupled to each other. So, some reviews of used common technique in order to solve this problem have been made as well. However, to ensure the selected motor candidates operates efficiently, some reviews regarding of advantages and disadvantages for different control methods also has been discussed. It is emphasized that different speed control method has its own achievement.
2.6.1 Sinusoidal type of PMSM selection

PM motor drives have been a topic of interest for the last twenty years. Different authors have carried out modelling and simulation of such drive. From the review has been made since 1995 for PMSM Drive System, there were several of controllers, method or technique has been proposed. Most of the researchers focus on the controller in order to improve the PMSM drive system.

In motion control applications PMSM have been widely used in [8][11][24][26][30][37][39][40] but among these, the IPMSM have been of a particular attention due to their distinct features of high power density and low-torque ripples [12][41]. This is because with permanent magnets entombed inside the rotor, characteristic such as smooth reduced air-gap and rotor surface will result in a robust mechanical construction and thus better dynamic performance and allowing higher speed with quiet operation [41]. Other than that, due to IPMSM’s advantages which are high torque to current ratio, high power to current ratio, high efficiency, low noise and robustness make IPMSM quite popular used nowadays [42].

IPMSM having low efficiency in low speed range but the efficiency can be increase by using concentrated winding as proposed in [43] in which copper loss is more predominant than core loss. However, because of that the IPMSM might become worse in high speed region [44]. Furthermore, IPMSM is a three phase motor that excited on the stator windings, which create a rotating magnetic field that interacts with two or more salient poles of a permanent magnet rotor. From there it gets very complicated. Other than that, the IPMSM has inverse saliency which is L4 < L4 and both reluctance and the magnet thrust with the leading current control are produced. It’s different with SPMSM, which has no saliency and only magnet thrust is produced [45]. By these reasons, SPMSM has been selected.

2.6.2 Variable speed control motor selection

Like any other AC machine, PMSM is a strongly coupled system. Its internal electromagnetic relation is very complex [46][47]. However, there are several types of technique has been proposed among the researchers in order to control AC motors especially PMSM for variable speed applications.
Open loop scalar based control is one way of controlling AC motors for variable speed applications which represent the most popular control strategy of squirrel cage AC motors. Running in a sensorless mode is the most advantage of this simple method because information about the angular speed or actual rotor position does not need to the control algorithm [48]. On the contrary, the big disadvantage is the speed dependence on the external load torque and it will effect to dynamic performance.

P. D. C. Perera [30] proposed stabilizing technique for PMSM without damper windings in the rotor or in other word is sensorless controller which is required no position sensor or other type of extra sensor to select gain for stabilizing loop for stable operation in a wide frequency range. The problem is difficulty consists of state estimation at very low speeds where the base excitation is low and the observer performance inclined to be poor.

Another way of controlling AC motors for variable speed applications is Field Oriented Control (FOC) or Vector Control (VC). FOC is mostly used as it provides superior torque to inertia ratio, high controllability and greater power density as in [8][12][30][37][40][41][49]. FOC using coordinate transformation is commonly adopted in high performance PMSM drive technology. In synchronous motor, the original nonlinear structures are coupled to each other and converted into a decoupled linear control structure [50]. Dynamic model of the PMSM and its control scheme is simpler by utilizing the FOC technique. The product of stator current and PM rotor flux is generated proportional to electromagnetic torque. High performance similar to separately excited DC motor is produce due to the two components are orthogonal [37]. So, the PMSM is very useful in applications and FOC of PMSM is very popular kind of its control.

2.6.3 FOC of PMSM drive system with conventional speed controller

In order to improve the performance of PMSM drive system, an analysis of the FOC for a PMSM drive system previous work with conventional speed controller is being discussed in advance. The performance of PMSM which requires quick transient response must be improved, as the PMSM motor is replacing the conventional dc motor for small output power rating variable speed control system [51]. Proportional
integral (PI) and proportional integral derivative (PID) controllers are traditionally handled and commonly used by conventional controllers. The PID controller's parameters are determined in an optimal way by the known methods Zeigler Nichols and poles assignment. This conventional controller is used either in open or closed loop application.

A comprehensive performance analysis on the principle of operation, design considerations and control algorithms of FOC for a PMSM drive system and PID for speed control in close loop operation is proposed by Puspendo Maji [52]. The FOC system is enabled with PID replacing PI from standard model in this paper. PID controllers and FOC method are classically used to perform speed control of typical PMSM drives. The block diagram of FOC control of PMSM that the author proposed is shown in Figure 2.4. Standard model that provides pulse to the inverter is the SVPWM. The orientation of pulse from FOC to PMSM is subjected to monitoring and control, made feasible by PID controllers. It is popularized that control properties of PID controller is far superior in consideration with PI controller. The result is verified by simulation.

![Block diagram of FOC control of PMSM](image)

**Figure 2.4 Block diagram of FOC control of PMSM**

While, Huazhong Xu [53] proposed a vector control strategy of PMSM based on Pan-Boolean algebra self-adapting PID control which is unnecessary to set up the exact mathematical model of the controlled plant. It is able to eliminate the influences of the parameters of the controlled plant and the disturbance of the external environment by online adjusting the parameters of the PID controller according to the deviation and deviation rate at different time. Simulation based on Matlab and implemented using experimental platform based on DSP chip is used to verify the effectiveness of the proposed control method. The performance and
robustness of the controller are better than the conventional PI controller in the PMSM control system based on the simulation and experimental results.

It’s different to Wang Song [54] which is proposed a method of building two closed-loops vector control simulation model for PMSM. He chooses non-linear PID in speed loop as a composite control strategy which consists of a PID controller, a PI controller and a switch device. The controller will take speed error as the switching condition when it is less than the certain value, select PI controller to work, otherwise, select PID controller. The authors prove that by using the proposed method, it can not only reduce speed pulsation and overshoot but also quicken the simulation remarkably.

PMSM drive with the vector control has been widely and successfully applied to servo tasks. However, vector control PMSM drive with conventional controllers has difficulty dealing with dynamic speed tracking, parameter variations and load vibration. With the conventional PID regulator, the parameters variation and nonlinearities of the PMSM deteriorate control performance in dynamic process, cause torque and speed pulsation, which limits the PMSM drive as a high precision servo [55]. In addition, the controlled plant often changes with the working condition and make it not suitable for some higher precision requirement situations [56]. Even though in practical conditions PID controller has been dominating the control system of PMSM, however the performance of PMSM using PID controller is not always satisfactory [57].

2.6.4 FOC of PMSM drive system with artificial intelligent speed controller

In a high performance drive system, not only a fast and accurate response is required, but also the ability of quick recovery of the speed form any disturbances and insensitivity to parameter variation are essential [58]. On another aspect, artificial neural networks (ANN) and fuzzy logic systems (FL) have been known as powerful tools capable of providing robust approximation for mathematically ill-defined systems that may be subjected to structured and unstructured uncertainties.

Fuzzy proportional-integral-derivative and Fuzzy Proportional-Integral for speed control in closed loop operation are proposed in [40] and [49]. They found that by using FL provides a better response to the drive system. Bhim Singh [40] verified
him proposed design with the analysis and hardware implementation by using DSP (ADMC401). From the result obtain, it is shows that the system response is smooth and there are no oscillations in the case of speed reversal. Other than that, the authors also prove that the implementation on DSP has resulted in the use of reduced hardware and improved dynamic behaviour, reduce offset error, minimize control delays and perform high resolution control.

While, A. Chandra [49] developed the model along with FL PID by simulation only in order to examine the dynamic behaviour of the PMSM drive system. Based on the simulation result, it shows that the proposed scheme has confirmed that there are quick and instantaneous with any disturbance in the set operating parameters of the drive system.

A novel implementation of speed controller based on adaptive FL is presented by Chunhua Zang in order to improve the dynamic performance of PMSM drive. Value [-1 1] are normalized to the universe of all input and output variables. The PMSM drive with the proposed control scheme has the merits of simple structure, robustness, quick tracking performance based on the simulation result [59].

Even though, FL need more fine tuning and simulation before operational. Despite that, FL controller also have difficulties in tuning the parameters of the membership function according to changes in the system and in determining appropriate control laws. This point is also supported by [60] that the number of rule base and scaling factor determination have great influence in obtaining the strength of FL controller by varying parameters in terms of shape of membership function with intention to attain the desired performance. However, some rules fired weakly do not contribute significantly to the final decision and may be reduced since all fuzzy rules contributes to some degree to final inference or decision [61].

Apart from FL controller, ANN is also used in drive system such as proposed in [11] and [41]. These papers presents the performance of an artificial-neural-network (ANN) with initial estimation is obtained by off-line training method for drive system accurate speed control but online training has been carried out to update the ANN. The identification of PMSM using ANN that Rajesh Kumar proposed in [11] is shown in Figure 2.5. It consists of input layer, output layer and two hidden layers. By comparing the actual and estimated speeds as calculated by equations, the performance of the trained ANN identifier is evaluated by simulation result. Based
on the results, the unknown, time invariant, nonlinear characteristics of the PMSM and its load have been successfully capture by the ANN.

![Diagram](image)

Figure 2.5 Identification of PMSM using ANN

Yang Yi [41] proposed novel dynamic ANN controller for accurate speed control of IPMSM under system uncertainties as shown in Figure 2.6. The proposed architecture of a two-layer (M=2) feed-forward ANN. By using off-line training method, ANN speed controller is obtained. Under continuous mode of operation, on-line training has been carried out to update the ANN. The capability of the ANN as a speed controller for high performance drive systems has been verified both theoretically and experimentally for a laboratory IPMSM drive. From the results, it is observed that the ANN speed controller can adaptively tackle the problems of parameter changes and load variations, and enables the drive system to follow the reference speed quite precisely.
But it’s different with C. Baoping [39] that proposed influence of switching frequency of power switch on the performance and hidden layer neurons of ANN for PMSM. So, the author finds that by using an algorithm of SVPWM based on ANN, the PMSM generates less current harmonic distortion and pulsating torque by choosing the optimum hidden neurons.

While in [37], Fayez F.M. El-Sousy proposed high-performance robust hybrid speed controller of PMSM drive. The author combines the two-degrees of freedom integral plus proportional (2DOF I-PD) and the Neural Network (NN) model following controller (NNMFC) in order to become conscious of high dynamic performance in load disturbance, present a rapid, robust performance and precise response. However, unit control of several single DOF motors is actualized created multiple DOF by with complex mechanical transmission mechanism, which cause complexity in mechanical structure, bulkiness in volume, slow response, low positioning precision and dynamic performance [62].

Ben Guo [63] has proposed a modified model predictive direct speed control (MP-DSC) based on NN as shown in Figure 2.7. The author use sliding-window (SW) NN learning framework or known as online batch learning method with the time varying tracking properties of recursive learning in order to merge the robustness of batch learning. Not only achieve promising dynamic and steady behaviour, excellent adaptability to parameter perturbation and external disturbance of proposed control strategy have been verified by simulation and experiment as well.
A robust ANN based nonlinear speed observer for PMSM was introduced by Hicham Chaouin [64]. By using back-propagation learning algorithm, a multilayer perception is trained online to estimate the rotor speed without any appropriate dynamics knowledge. Since it is not based on a linear-in-parameters model, thus the proposed observer is able to cope with higher degrees of nonlinearity, unlike many neural network observers. Therefore, robustness to parameter variations is achieved. The performance of the proposed observer in the presence of high parametric uncertainties is highlighted by simulation results for different situations. The proposed observer is reliable and effective for PMSM drives.

Tomasz Pajchrowsk [65] has presented the synthesis and the properties of the Neural speed controller trained online. The block diagram of proposed control is shown in Figure 2.8. For the training process of the ANN, the resilient backpropagation (RPROP) algorithm was chosen. In order to improve controller operation, the algorithm was modified. Results of both simulation and experimental research by the specific properties of the controller, i.e., adaptation and auto-tuning, are illustrated. Due to its impressive dynamics, an electric drive with PMSM was chosen for experimental research. The obtained results indicate that the presented controller may be implemented in industrial applications.
A combination of a dynamic Diagonal Recurrent NN (DRNN) PID controller with a traditional PID controller applying in the PMSM servo system is designed by Liying Hu [66]. A perfect performance under variable parameters and torque disturbance, the servo system with traditional PID controller can’t achieve it. For controlling complicated servo system, DRNN has a good learning ability with a simple and recurrent structure, so it is suitable. The matrix is transformed to the diagonal matrix in DRNN, so it is very suitable for the real-time control system which greatly simplifies the computation. To achieve a fast convergence, a dynamic BP (DBP) algorithm is used in the DRNN controller. Simulation results show the compound control method can improve the dynamic response performance and enhance the static precision compared to the traditional PID controller.

From all the papers has been review, the robustness and ability of quick recovery of the speed from parameter variation or unknown and any disturbance was improved by using ANN. This is because the ANN techniques of learning and control provide a natural framework for the design of online controllers for drive systems having unknown or uncertain dynamics. To approximate nonlinear functions is the most significant ability of ANN. In other words, ANN are characterized by their nonlinear behaviour, parallel processing and their automatic optimization and learning capabilities [64].
Gap of study

The gap of study can be seen obviously from the comparison between the research work presented in this thesis and the previous work performed by other researchers in the Table 2.1. The gaps of study are categorized based on motor type, speed controller and result observation that other researcher proposed.

Since PMSM are classified into two groups which are SPMSM and IPMSM, there are five out of eight researchers have chosen SPMSM based on the Table 2.1. While in term of the speed controller, PI, PID, Fuzzy and ANN are choosing to preserve the good performance drive system. Utilisation of the proposed method is used in different ways among all the researchers. For example, researcher in [63] used ANN for sliding window learning framework in order to update the datum in the window and the result is focused on speed only. While, researcher used online learning ANN as observer to calculate the rotor position in order reduce sensor in [64] and the result is focus on speed and error. Researcher in [59] uses Fuzzy is used as speed controller to improve dynamic performance of PMSM drive system and the result is compared to PI speed controller based on speed, d-q current and torque. Then, researcher in [52] uses only conventional controller which is PID as the speed controller and the result is not well achieved to reference speed given. For the researcher in [66] uses different type of ANN which is Recurrent NN that allowed cyclic connection with offline learning procedure and the result is compared to PID based on speed and rotor position. In [41], the researcher used online learning ANN as speed controller but only focused on speed and d-q current as the result observation without any comparison with other speed controller. It is same with researcher in [11] that only focused on speed as result observation without any comparison with other speed controller but offline learning ANN has been proposed as the speed controller. While, researcher in [65] used online learning ANN as speed controller then observe the speed together with error and compared among online learning itself during auto tuning and adaptation of tolerance band.

However, it is proved that speed controller is an important part in drive system to ensure the speed of the machine can be matched to the need. ANN is one of the powerful tools to achieve good performances drive system. This is because ANN more simple architecture and no need data parameter compared to Fuzzy. By
REFERENCES


