

# **Implementation of Intelligent Controller for Permanent Magnet Synchronous Motor**

A Dissertation Submitted In Partial Fulfillment of the Requirements for the Degree of

**MASTER OF TECHNOLOGY**

**IN**

**CONTROL AND INSTRUMENTATION**

Submitted by

**K RAVINDRANATH**

**2K11/C&I/04**

Under the Guidance of

**PROF. MADHUSUDAN SINGH**



**ELECTRICAL ENGINEERING DEPARTMENT**

**DELHI TECHNOLOGICAL UNIVERSITY**

**(FORMERLY DELHI COLLEGE OF ENGINEERING)**

**BAWANA ROAD, DELHI-110042**

**JULY – 2013**

# Certificate

This is to certify that the dissertation title “**Implementation Of Intelligent Controller For Permanent Magnet Synchronous Motor**” is the record of the work carried out by **K RAVINDRANATH** under my guidance and supervision in the partial fulfillment of the requirements for the award of the degree of Master of Technology in Control and Instrumentation in the Department of Electrical Engineering at **Delhi Technological University, Delhi**. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any other degree or diploma.

(Prof. Madhusudan Singh)

Department of Electrical Engineering

## **Acknowledgement**

It would not have been possible to write this thesis without the help and support of the some people around me. It would be inappropriate on my part if I won't express my gratitude. So here I whole heartedly thank all the people who have helped me one way or the other.

First and foremost I would like to thank Prof. Madhusudan Singh, my project guide and also the Head of the Department, Electrical Engineering. Who is one of the most genuine person I have ever seen. I am really lucky to have him as my guide through whom I have learned a lot by observing him. Which would be greatly useful in future ahead, I Sincerely will try to follow some his values.

I also want to express my gratitude to Shoeb hussain my classmate who has helped me a lot in explaining things which are necessary to complete my project work.

At last, but the most important I would like to thank my family, especially my dad who is an inspiration to me and my brother without whom may be, it wouldn't have been possible for me to pursue my graduation and reach thus far.

K RAVINDRANATH

Roll no. 2K11/C&I/04

M.Tech (Control & Instrumentation)

## **Abstract**

The thesis deals with the implementation of intelligent controller for permanent magnet synchronous motor drive system in MATLAB/Simulink. With the introduction of permanent magnets of high flux density as well as a high coercivity in the late eighties, synchronous motors with permanent magnets became an attractive alternative for application in high performance variable speed drives. In the power range of a few kW to several tens of kW, the sinusoidal excited permanent magnet synchronous motor (PMSM) is preferred to brushless DC motor (BLDC). In the past few decades various control methods have been reported to control torque and speed of three phase PMSM. In the present work the field oriented control is used for the operation of the drive. It allows a decoupled control of electromagnetic torque control and the motor flux, and hence the PMSM is operated as separately excited DC motor. Therefore, it is preferred to use it in high performance motor applications.

The operations of PMSM with different controllers like PI, fuzzy and predictive current controllers (PCC) are analyzed for speed control. A complete mathematical model of the PMSM drive has been developed and implemented in MATLAB/Simulink. The operation of the drive with conventional PI controller is initially studied and efforts have been made to improve the dynamic performance of the drive using Fuzzy and Predictive control. The necessary rule base of fuzzy controller is designed and implemented using fuzzy tool box in MATLAB.

## List of Symbols

B	friction
BLDC	Brushless DC Motor
d-axis	Direct axis or Polar axis
q-axis	Quadrature axis or Interpolar axis
$i_a, i_b, i_c$	Three phase currents
$i_d$	d-axis current
$i_f$	Equivalent permanent magnet field current
$i_q$	q-axis current
$I_m$	Peak value of supply current
IGBT	Insulated Gate Bipolar Transistor
IPM	Interior Permanent Magnet
J	inertia
L	self-inductance
$L_d$	d-axis self inductance
$L_q$	q-axis self inductance
$L_{ls}$	Stator leakage inductance
$L_{dm}$	d-axis magnetizing inductance
$L_{qm}$	q-axis magnetizing inductance
$L_s$	equivalent stator self-inductance per phase

P	Total number of poles
PI	proportional integral
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
$R_s$	stator resistance per phase
SPM	Surface Permanent Magnet
$T_e$	develop torque
$T_L$	load torque
$v_a, v_b, v_c$	Three phase voltage
$v_d$	d-axis voltage
$v_q$	q-axis voltage
VSI	Voltage Source Inverter
$\rho$	derivative operator
$\lambda_d$	flux linkage due to d-axis
$\lambda_f$	PM flux linkage or Field flux linkage
$\lambda_q$	flux linkage due to q-axis
$\theta_r$	rotor position
$\omega_r$	rotor speed
$\omega_m$	electrical speed
$\omega_{rated}$	motor rated speed

## List of Figures

- Fig. 2.1 Flux Density versus Magnetizing Field of Permanent Magnetic Materials
- Fig. 2.2 Surface Permanent Magnet Motor
- Fig. 2.3 Interior Permanent Magnet Motor
- Fig. 2.4 Voltage Source Inverter Connected to a Motor
- Fig. 2.5 PWM current controller
- Fig. 2.6 Hysteresis controller
- Fig. 2.7 Position control mode block diagram
- Fig. 2.8 Torque control mode block diagram
- Fig. 3.1 Motor Axis
- Fig. 3.2 Permanent Magnet Motor Electric Circuit without Damper Windings
- Fig. 3.3 Diagram showing variable frequency control types
- Fig. 3.4 Block diagram representing vector control scheme
- Fig. 3.5 Proportional Integral Controller block diagram
- Fig. 3.6 Functional block diagram of Fuzzy Logic Controller
- Fig. 3.7 Input and Output membership function representation
- Fig. 3.8 Fuzzy incremental controller
- Fig. 4.1 Simulink Model of VCPMSM with (a) PI Controller (b) Fuzzy Logic Controller (c) Predictive control
- Fig. 4.2 Performance analysis of VCPMSM using PI for (a) no load (b) load applied at  $t=0.1$  sec
- Fig. 4.3 Performance analysis of VCPMSM using FLC controller for (a) no load (b) load applied at  $t=0.1$  sec

Fig. 4.4 Performance analysis of VCPMSM using Predictive controller for (a) no load (b) load applied at  $t=0.1$  sec

Fig. 4.5 Comparison of Speed deviation in PI, Fuzzy and Predictive current Controllers



## Table Of Contents

Certificate	II
Acknowledgement	III
Abstract	IV
List of symbols of used	V
List of figures	VII
<b>Chapter 1 Introduction</b>	
1.1 General	1
1.2 Literature Survey	2
1.2.1 Permanent magnet motors	2
1.2.2 Direct torque control	2
1.2.3 Vector control	4
1.2.4 Sensorless control	6
1.2.5 Predictive current control	7
1.3 Objective of present work	8
1.4 Conclusion	8
<b>Chapter 2 Permanent magnet synchronous motor drive system</b>	
2.1 Introduction	9
2.2 PMSM drive system	9
2.3 Permanent Magnet Synchronous Motor	9

2.3.1 Permanent magnet materials	9
2.3.2 Classification of Permanent magnet motors	10
2.3.2.1 Direction of field flux	10
2.3.2.2 Flux density distribution	11
2.3.2.3 Permanent magnet radial field motors	11
2.4 Position sensor	13
2.5 Current controlled VSI	13
2.5.1 Three phase VSI	13
2.5.2 Current control	15
2.5.2.1 PWM current controller	15
2.5.2.2 Hysteresis current controller	16
2.6 Control modes of PMSM	17
2.6.1 Position control mode	17
2.6.2 Speed control mode	17
2.6.3 Torque control mode	18
2.7 Conclusion	18
<b>Chapter 3 Mathematical Modeling of PMSM</b>	
3.1 Introduction	19
3.2 Detailed modeling of PMSM	19
3.2.1 Parks transformation	21
3.2.2 Equivalent circuit of PMSM	22

3.3 PM motor control	22
3.3.1 Scalar control	23
3.3.1.1 Voltage/Frequency	23
3.3.2 Vector control	24
3.3.2.1 vector control of PMSM	25
3.4 Field oriented control of PM motor	26
3.4.1 Constant torque-angle control	27
3.4.2 Flux weakening control	28
3.5 Speed control of motor	28
3.5.1 PI controller	28
3.5.2 FLC controller	29
3.5.2.1 Fuzzification	30
3.5.2.2 Knowledge base and Inference stage	32
3.5.2.3 Defuzzification	32
3.5.2.4 Tuning FLC	33
3.5.3 Predictive control	33
3.5.3.1 Difference between classic and predictive controls	34
3.5.3.2 Predictive current controller	34
3.6 Conclusion	36

## **Chapter 4 Simulation Results**

4.1 General	37
4.2 Matlab Model	37
4.3 Performance Analysis of VCPMSM using PI controller	39
4.4 Performance Analysis of VCPMSM using FLC	41
4.5 Performance Analysis of VCPMSM using Predictive control	42
4.6 Comparison of VCPMSM using PI ,FLC and Predictive Current speed controller	44
4.6.1 Comparison of PI, FLC and PCC under various operating condition	45
4.7 Conclusion	46

## **Chapter 5 Conclusion and Future scope of work**

5.1 Main Conclusion	47
5.2 Future scope of work	47
References	49

# Chapter 1

## INTRODUCTION

### 1.1 General

In recent years the efficient operation of ac drive has become a prominent area of research for efficient use of electricity, the apparatus are designed and manufactured to reduce the energy consumption AC drives are commonly used in motion control system of modern industry. In electrical machine the efficiency optimization is possible by changing the machine type, structure or improving the control of the machine. AC motor with simple construction, reliable operation and less cost are being developed in the recent period. Variable speed AC drives has applications like robotics, electric vehicles, air conditioning, machine tools and process control etc.

Synchronous machines are used now for application ranging from high power to low power. From this class of machines Permanent Magnet Synchronous Machines (PMSM) are very advantageous and challenging.

The main advantage of PMSM consists is its reluctance torque along with high efficiency, high power factor and wide range of speed control. Also since the rare earth PM material and technology has reduced the price of the magnets, PMSM are available in the market at low cost. Weight and size have been reduced, keeping the same output power. Low inertia rotor provides better dynamic response of the motor.

The dynamic response of the motor mainly includes its speed and torque variation under different operating condition. The operation of PMSM in forward and reversing motoring are available in the literature. There are two main techniques which are used for controlling of the speed of a motor. They are scalar control and vector control technique. In the present work vector control technique has been discussed. Which is an advancement of the scalar control technique. The vector control overcomes certain disadvantages which are present in scalar control such as poor dynamic performance,

with high overshoot etc.

A closed loop speed control of PMSM using conventional speed controller has been designed. For further improvement of performance of drive, intelligent controllers like Fuzzy and Predictive controller are being used. Predictive current control technique is one of latest techniques used in efficient operation of PMSM. Implementation has been done in MATLAB/Simulink.

## **1.2 Literature Survey**

PM motor drives have been a topic of interest for few decades. A vast variety of literature, in the form of books, research papers and industries application notes are available. A brief overview of few important literature is described.

### **1.2.1 Permanent magnet motors**

R.KRISHNAN [18], presented basics about Permanent magnet synchronous motor (PMSM) and brushless dc motor (BLDC). The salient features between two motors have been described. Vector control and various control strategies have been proposed, for closed loop operation of PMSM drives. The dynamic and steady state equations of PMSM have been presented.

Bose, B. K. [20], presented different types of synchronous motors and compared them to induction motors. The modeling of PM motor was derived from the model of salient pole synchronous motor. All the equations were derived in synchronously rotating reference frame and was presented in the matrix form. The equivalent circuit was presented with damper windings and the permanent magnet was represented as a constant current source. Some discussions on vector control using voltage fed inverter are also available.

### **1.2.2 Direct Torque Control**

Zhong, M. F. Rahman [13], discussed the direct torque control (DTC) for permanent magnet synchronous motor (PMSM) drives. It is mathematically proven that the increase of electromagnetic torque in a permanent magnet motor is proportional to the increase of

the angle between the stator and rotor flux linkages and therefore, the fast torque response can be obtained by adjusting the rotating speed of the stator flux linkage as fast as possible. It is also shown that the zero voltage vectors should not be used and stator flux linkage should be kept moving with respect to the rotor flux linkage all the time. The implementation of DTC in the permanent magnet motor is discussed, and it is found that for DTC using currently available digital signal processors (DSP's), it is advantageous to have a motor with a high ratio of the rated stator flux linkage to stator voltage.

Yasser Abdel, Rady Ibrahim Mohamed [43], discussed direct instantaneous torque control scheme for a direct drive (DD) permanent magnet synchronous motor (PMSM). A hybrid control structure combining the internal model principle and the variable structure control (VSC) approach is proposed. First, a variable structure torque controller is adopted to regulate the torque angle increment according to the torque feedback error. Second, the appropriate control voltage vector is determined using the reference stator flux vector and the estimated dynamic back electromotive force (EMF) vector, as an internal model, in a deadbeat control manner. Subsequently, better disturbance rejection is obtained with the proposed cascaded control structure. To obtain the instantaneous torque and flux information, a robust adaptive motor model is proposed. The Lyapunov stability theory is used to analyze the stability of the augmented robust adaptive motor model and to give a guideline for tuning model parameters.

Jawad Faiz, S. Hossein Mohseni [25], proposed that a permanent-magnet synchronous machine (PMSM) can be controlled using the direct torque control (DTC) technique in three different ways, i.e. by controlling flux, reactive torque and rotor d-axis current. Frequently, the DTC technique controls the speed of the motor by controlling stator flux with the aim of obtaining an optimal torque. A varying flux, proportional to the torque may be used instead of a fixed flux, resulting in a maximum torque per ampere or maximum torque per flux (MTPF). A reference-flux-generating method is followed to achieve the MTPF. An approximate equation is then derived using numerical techniques in order to obtain the reference flux from the torque. This equation is then applied to the DTC control system in order to obtain the reference flux. The control scheme has been verified by simulation and tests on a salient-pole permanent-magnet synchronous motor.

Hao Zhu, Xi Xiao and Yongdong Li [49], discussed torque ripple reduction of the torque predictive control scheme for PMSM. The direct torque control (DTC) technique of permanent-magnet synchronous motors (PMSMs) receives increasing attention due to its advantages in eliminating the current controllers and quicker dynamic response, compared with other motor control algorithms. However, high torque and stator flux ripples remain in the system when using DTC technologies. This means large stator voltage and current harmonic contents exist in the PM motors. Since the variation of motor electromagnetic torque is related to the voltages that are applied to the motor, by analyzing the relationships between stator flux, torque, and voltages, a PMSM torque predictive control scheme is proposed. The proposed scheme is simulated and experimentally verified. Both simulation and experimental results have shown that low torque ripple and reduced stator current harmonics are achieved by using the proposed scheme.

### **1.2.3 vector control**

Sebastian, T., Slemon, G. R. and Rahman, M. A. [2], reviewed permanent magnet synchronous motor advancements and presented equivalent electric circuit models for such motors and compared computed parameters with measured parameters. Experimental results on laboratory motors were also given.

Jahns, T.M., Kliman, G.B. and Neumann, T.W. [4], discussed that interior permanent magnet (IPM) synchronous motors possessed special features for adjustable speed operation which distinguished them from other classes of ac machines. They were robust high power density machines capable of operating at high motor and inverter efficiencies over wide speed ranges, including considerable range of constant power operation. The magnet cost was minimized by the low magnet weight requirements of the IPM design. The impact of the buried magnet configuration on the motor's electromagnetic characteristics was discussed. The rotor magnetic saliency preferentially increased the quadrature-axis inductance and introduced a reluctance torque term into the IPM motor's torque equation. The electrical excitation requirements for the IPM synchronous motor were also discussed. The control of the sinusoidal phase currents in magnitude and phase



angle with respect to the rotor orientation provided a means for achieving smooth responsive torque control. A basic feed forward algorithm for executing this type of current vector torque control was discussed, including the implications of current regulator saturation at high speeds. The key results were illustrated using a combination of simulation and prototype IPM drive measurements.

Pillay and Krishnan, R. [5], presented PM motor drives and classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BLDC) drives. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BLDC has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. The PMSM is very similar to the wound rotor synchronous machine except that the PMSM that 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. Hence the d, q model of the PMSM can be derived from the well-known model of the synchronous machine with the equations of the damper windings and field current dynamics removed. Equations of the PMSM are derived in rotor reference frame and the equivalent circuit is presented without dampers. The damper windings are not considered because the motor is designed to operate in a drive system with field-oriented control. Because of the non-sinusoidal variation of the mutual inductances between the stator and rotor in the BLDC, it is also shown that no particular advantage exists in transforming the abc equations of the BLDC to the d, q frame.

As an extension of his previous work, Pillay, P. and Krishnan, R. [6], presented the permanent magnet synchronous motor (PMSM) which was one of several types of permanent magnet ac motor drives available in the drives industry. The motor had a sinusoidal flux distribution. The application of vector control as well as complete modeling, simulation, and analysis of the drive system were given. State space models of the motor and speed controller and real time models of the inverter switches and vector controller were included. The machine model was derived for the PMSM from the wound rotor synchronous motor. All the equations were derived in rotor reference frame and the equivalent circuit was presented without dampers. The damper windings were not

considered because the motor was designed to operate in a drive system with field-oriented control. Performance differences due to the use of pulse width modulation (PWM) and hysteresis current controllers were examined. Particular attention was paid to the motor torque pulsations and speed response and experimental verification of the drive performance were given.

Pillay and Krishnan [7], discussed application characteristics of permanent magnet synchronous and brushless dc motors for servo drives. Where they stated Guidelines for the appropriate machine to be used for a given application.

#### **1.2.4 Sensorless control**

Mohamed Rashed, Peter F. A [39], proposed Sensorless indirect rotor field orientation speed control of a permanent-magnet synchronous motor with stator resistance estimation. Efficient and precise sensorless speed control of a permanent magnet synchronous motor (PMSM) requires accurate knowledge of rotor flux, position, and speed. This is guaranteed by detecting the back electromotive force (EMF). However, these schemes show great sensitivity to stator resistance mismatch and system noise, particularly, during low speed operation. The stator resistance and the rotor-flux speed and magnitude are estimated adaptively using stable model reference adaptive system estimators. Simple stability analysis and design of the estimators are performed using linear-control theory applied to an error model of the PMSM in a synchronous rotating reference frame. The convergence of rotor position- and speed-estimation errors to zero is guaranteed.

Mongkol Konghirun, Longya Xu [37], discussed a fast transient-current control strategy in sensorless vector-controlled permanent magnet synchronous motor the technique can guarantee the current vector transition from one operating point to another with minimum time. Compared to a proportional-integral controller, the current response by using the time-optimal controller is much faster, even under a limited dc bus voltage. Experiments are carried out to substantiate the proposed technique

Todd D. Batzel, Kwang Y. Lee [32], proposed electric propulsion with sensorless permanent magnet synchronous motor of the electric machine configurations available for vehicle propulsion applications, there has been considerable interest in the PMSM. This attention is primarily due to the PMSM's superior power density, outstanding efficiency, and potential for quiet operation as compared to the IM and synchronous reluctance machine. The development of a sensorless PMSM drive prototype for undersea propulsion is discussed with particular attention given to the implementation details and overall drive performance under various operating conditions

### **1.2.5 Predictive control**

Hyung-Tae Moon, Hyun-Soo Kim [22], explained A discrete time predictive current control for PMSM , a new predictive current controller for a permanent magnet synchronous motor (PMSM) considering delays is presented. In a full digital current control system for a PMSM, there are inevitable delays in calculating and applying the inverter output voltages to the motor terminals. A predictive current controller implemented in a full digital system has serious problems such as the oscillation and large overshoot. A discussion of compensation methods to cope with the nonlinearities of the real system is also presented.

Florent Morel, Xuefang Lin-Shi [46], discussed the comparative study of three predictive current control schemes for permanent-magnet synchronous machine (PMSM) drives. The first control scheme predicts the future evolution of the currents for each possible configuration of the inverter legs. Then, the switching state which minimizes a given cost function is selected and applied during the next sampling time. The second control scheme uses a modulator to apply two configurations of the inverter legs during a computation period. The third control scheme uses a model of the PMSM in order to predict the stator voltage which allows us to reach the desired currents after one modulation period. A simulation study is performed in order to compare sensitivity to parameters of each control scheme.

Mitja Nemec, Klemen Drobic [47], proposed a modified method for direct current control (DCC) in a permanent magnet synchronous motor (SM). The control is performed using a predictive algorithm in rotor field coordinates due to its simpler implementation. Its task is to minimize the final current error at the end of the sampling interval. Depending on the desired performance, two variants are proposed, yielding either lower switching frequency or lower current ripple. Both variants of DCC, named DCC I and DCC II have been rearranged for applications in SMs with either surface-mounted permanent magnets or interior (buried) permanent magnets. A comparison with field-oriented control using space-vector modulation and synchronized on/off modulation shows the advantages and drawbacks of the proposed method.

### **1.3 Objective of the present work**

The present work deals with the speed control of three phase PMSM using intelligent controller.

1. A complete mathematical model of PMSM drive is developed and approximate Matlab models have been developed in MATLAB/Simulink.
2. The performance of PMSM using PI, Fuzzy logic controller (FLC) and Predictive current controller has been analyzed through simulation studies in MATLAB.

### **1.4 Conclusion**

The vector control scheme of the ac drives is one of the most widely used speed control techniques now-a-days. With the use of vector control technique an enhanced dynamic performance of PMSM drive is obtained. In the present work the implementation of intelligent controllers for PMSM is discussed. Further the chapter 2 of this thesis deals with drive system, chapter 3 with mathematical modeling of PMSM and in chapter 4 simulation results of this thesis have been shown using MATLAB/SIMULINK.

## **Chapter 2**

# **PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE**

### **2.1 Introduction**

The PMSM drives are an attractive option for various industrial applications such as packaging, machine tools, valve control in refineries etc. The PMSM drives are mainly operated on speed, position and torque control. A review of permanent magnet materials and classification of permanent magnet motors and basic configuration of PMSM drive are described in this chapter.

### **2.2 Permanent Magnet Synchronous Motor Drive System**

A PMSM motor drive consists of four main components, the PM motor, 3 phase voltage source inverter, controller unit and the position sensor.

### **2.3 Permanent Magnet Synchronous Motor**

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications.

#### **2.3.1 Permanent Magnet Material**

The properties of the permanent magnet material affect directly the performance of the motor and proper knowledge is required for the selection of the materials and for understanding PM motors.

The earliest manufactured magnet materials were hardened steel. Magnets made from steel were easily magnetized. However, they could hold very low energy and it was easy to demagnetize. In recent years other magnet materials such as Aluminum Nickel and Cobalt alloys (ALNICO), Strontium Ferrite or Barium Ferrite (Ferrite), Samarium Cobalt (First generation rare earth magnet) (SmCo) and Neodymium Iron-Boron (Second generation rare earth magnet) (NdFeB) have been developed and

used for making permanent magnets.

The rare earth magnets are categorized into two classes: Samarium Cobalt (SmCo) magnets and Neodymium Iron Boride (NdFeB) magnets. SmCo magnets have higher flux density levels but they are very expensive. NdFeB magnets are the most common rare earth magnets used in motors these days. A flux density versus magnetizing field for these magnets is illustrated in figure 2.1.

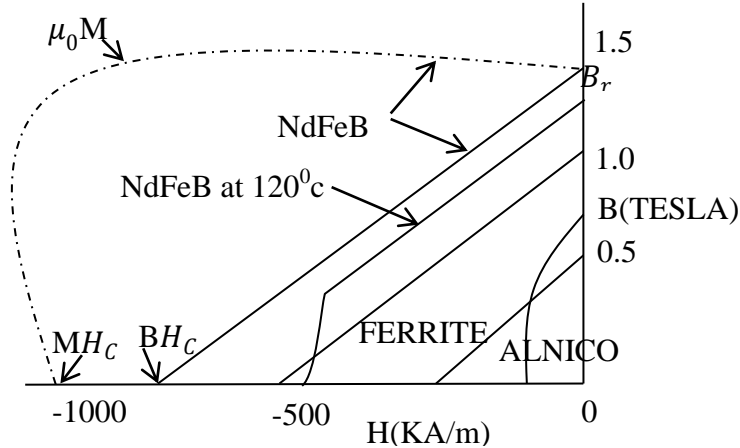


Figure 2.1 Flux Density versus Magnetizing Field of Permanent Magnetic Materials [18]

## 2.3.2 Classification of Permanent Magnet Motors

### 2.3.2.1 Direction of field flux

The permanent magnet (PM) synchronous machines can be broadly classified on the basis of the direction of field flux:

1. Radial field: the flux direction is along the radius of the machine.
2. Axial field: the flux direction is perpendicular to the radius of the machine.

The radial field PM machines are most commonly used. The axial field machines are coming into prominence in a small number of applications because of their higher power density and acceleration.

### **2.3.2.2 Flux density distribution**

PM motors are classified on the basis of the flux density distribution and the shape of current excitation. They are PMSM and PM brushless motors (BLDC). The PMSM has a sinusoidal-shaped back EMF and is designed to develop sinusoidal back EMF waveforms. They have the following:

1. Sinusoidal distribution of magnet flux in the air gap
2. Sinusoidal current waveforms
3. Sinusoidal distribution of stator conductors.

BLDC has a trapezoidal-shaped back EMF and is designed to develop trapezoidal back EMF waveforms. They have the following:

1. Rectangular distribution of magnet flux in the air gap
2. Rectangular current waveform
3. Concentrated stator windings

### **2.3.2.3 Permanent magnet radial field motors**

In PM motors, the magnets can be placed in two different ways on the rotor. Depending on the placement they are called either as surface permanent magnet motor or interior permanent magnet motor.

Surface mounted PM motors have a surface mounted permanent magnet rotor. Each of the PM is mounted on the surface of the rotor, making it easy to build, and specially skewed poles are easily magnetized on this surface mounted type to minimize cogging torque. This configuration is used for low speed applications because of the limitation that the magnets will fly apart during high-speed operations. These motors are considered to have small saliency, thus having practically equal inductances in both axes [18]. The permeability of the permanent magnet is almost that of the air, thus the magnetic material becoming an extension of the air gap. For a surface permanent magnet motor direct axis inductance is equal to quadrature axis inductance [18].

The rotor has an iron core that may be solid or may be made of punched laminations for simplicity in manufacturing. Thin permanent magnets are mounted on the

surface of this core using adhesives. Alternating magnets of the opposite magnetization direction produce radially directed flux density across the air gap. This flux density then reacts with currents in windings placed in slots on the inner surface of the stator to produce torque. Figure 2.2 shows the placement of the magnet.

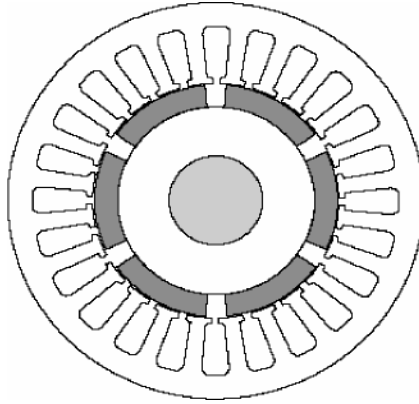


Figure 2.2 Surface Permanent Magnet Motor [18]

Interior PM Motors have interior mounted permanent magnet rotor as shown in figure 2.3. Each permanent magnet is mounted inside the rotor. It is not as common as the surface-mounted type but it is a good candidate for high-speed operation. 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  $L_q > L_d$ .

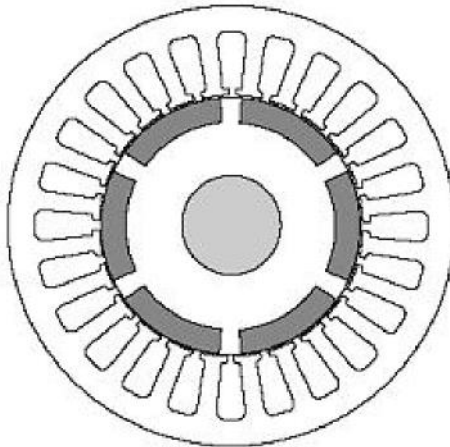


Figure 2.3 Interior Permanent Magnet Motor [18]



## 2.4 Position Sensor

Operation of permanent magnet synchronous motors requires position sensors in the rotor shaft when operated without damper winding. The need of knowing the rotor position requires the development of devices for position measurement. There are four main devices for the measurement of position, the potentiometer, linear variable differential transformer, optical encoder and resolvers. The ones most commonly used for motors are encoders and revolvers. Depending on the application and performance desired by the motor a position sensor with the required accuracy can be selected.

## 2.5 Current Controlled Inverter

The motor is fed from a voltage source inverter with current control. The control is performed by regulating the flow of current through the stator of the motor. Current controllers are used to generate gate signals for the inverter. Proper selection of the inverter devices and selection of the control technique will guarantee the effectiveness of the drive.

### 2.5.1 Three phase VSI

Voltage Source Inverter is a device that convert a DC voltage to 3 phase AC voltage of variable frequency and magnitude. They are very commonly used in adjustable speed drives and are characterized by a well-defined switched voltage wave form in the terminals [20] .Figure 2.4 shows a voltage source inverter.

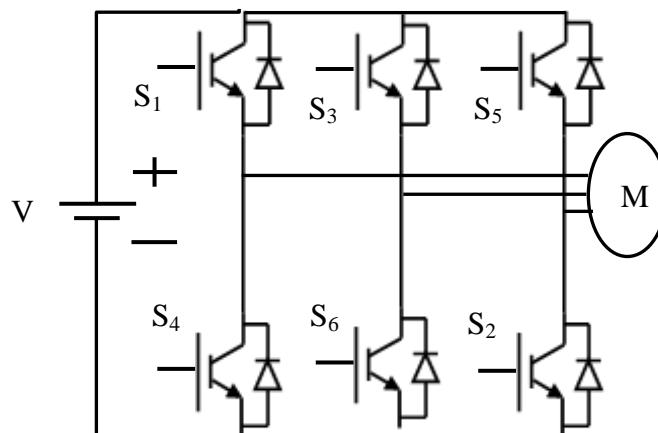


Figure 2.4 Voltage source inverter connected to a motor

The AC voltage frequency can be variable or constant depending on the application. Three phase inverters consist of six power switches connected as shown in figure 2.4 to a DC voltage source. The inverter switches must be carefully selected based on the requirements of operation, ratings and the application. There are several devices available today and these are thyristors, bipolar junction transistors (BJTs), MOS field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs) and gate turn off thyristors (GTOs). The devices list with their respective power switching capabilities is shown in table 2.1. While MOSFET is considered a universal power device for low power and low voltage applications, IGBT has wide acceptance for motor drives and other application in the low and medium power range. The power devices when used in motor drives applications require an inductive motor current path provided by antiparallel diodes when the switch is turned off.

IGBTs provide high input impedance and are used for high voltage applications. The high input impedance allows the device to switch with a small amount of energy and for high voltage applications the device must have large blocking voltage ratings. The device behavior is described by parameters like voltage drop or on-resistance, turn on time and turn off time.

Device	Power Capability	Switching Speed
BJT	Medium	Medium
GTO	High	Low
IGBT	Medium	Medium
MOSFET	Low	High
THYRISTOR	High	Low

Table 2.1 Power devices and switching capability

## 2.5.2 Current Control

The power converter in a high-performance motor drive used in motion control essentially functions as a power amplifier, reproducing the low power level control signals generated in the field orientation controller at power levels appropriate for the driven machine. High-performance drives utilize control strategies which develop signals for the AC machine currents.

Current controllers can be classified into two groups

1. Hysteresis current controller
2. PWM current controller.

Both types are discussed below.

### 2.5.2.1 PWM Current Controller

PWM current controllers are widely used. The switching frequency is usually kept constant. They are based in the principle of comparing a triangular carrier wave of desired switching frequency and is compared with error of the controlled signal. The actual speed ( $\omega_r$ ) of motor is compared to the desired speed ( $\omega_r^*$ ) and the error is further compared to the triangular carrier wave to generate switching signals. The comparison will result in a voltage control signal that goes to the gates of the voltage source inverter to generate the desired output. Its control will respond according to the error. If the error command is greater than the triangle waveform, the inverter leg is held switched to the positive polarity (upper switch on). When the error command is less than the triangle waveform, the inverter leg is switched to the negative polarity (lower switch on). This will generate a PWM signal like in figure 2.5. The inverter leg is forced to switch at the frequency of the triangle wave and produces an output voltage proportional to the current error command [20].

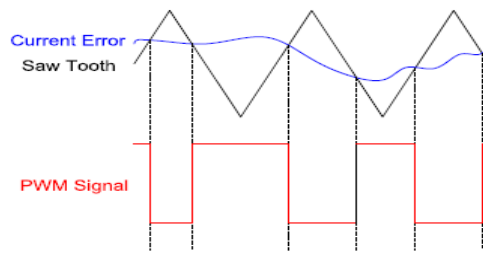


Figure 2.5 PWM current controller

### 2.5.2.2 Hysteresis current controller

Hysteresis current controller can also be implemented to control the inverter currents. The controller will generate the reference currents to the inverter within a range which is fixed by the width of the band gap. In this controller the desired current of a given phase is summed with the negative of the measured current. The error is fed to a comparator having a hysteresis band. When the error crosses the lower limit of the hysteresis band, the upper switch of the inverter leg is turned on. But when the current attempts to become less than the upper reference band, the bottom switch is turned on. Figure 2.6 shows the hysteresis band with the actual current and the resulting gate signals. This controller does not have a specific switching frequency and changes continuously but it is related with the band width [20].

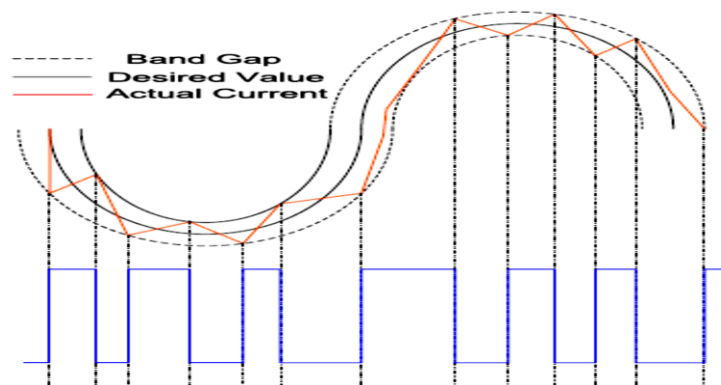


Figure 2.6 Hysteresis controller

## 2.6 Control modes of PMSM

The PMSM can be controlled in three different modes

- (i). Position control mode
- (ii). Speed control mode
- (iii). Torque control mode

### 2.6.1 Position control mode

Position control plays an important role in various areas such as automation industry, semiconductor industry, etc. For PMSM motor and position control, the initial position is required. By means of Hall sensors/encoders the rotor initial position can be identified. The position control consists two loops. The outer loop is position control to make the motor tracking and holding the given position. The inner loop is current control. Actually it is the torque control loop. The systems inner loop current regulation uses vector control and an outer loop of position regulation. This dual-loop structure ensures the fast torque response by using the vector control, high position accuracy and fast tracking performance with the position controller.

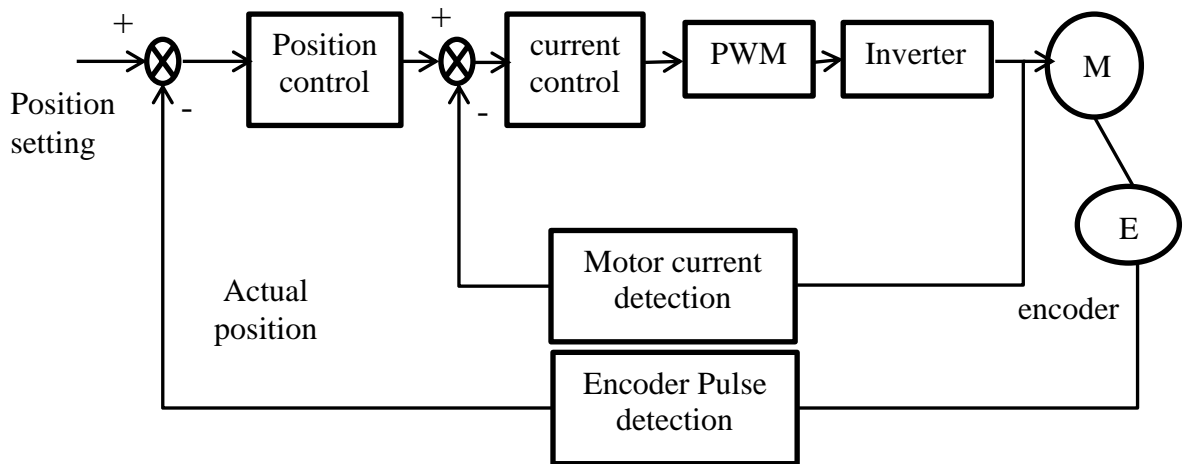


Fig 2.7 Position control mode block diagram

### 2.6.2 Speed control mode

Many applications, such as robotics and factory automation, require precise control of

speed and position. Speed Control Systems allow one to easily set and adjust the speed of a motor. The control system consists of a speed feedback system, a motor, an inverter, a controller and a speed setting device. A properly designed feedback controller makes the system insensible to disturbance and changes of the parameters. The purpose of a motor speed controller is to take a signal representing the desired speed, and to drive a motor at that speed. Closed Loop speed control systems have fast response, but become expensive due to the need of feedback components such as speed sensors. Speed control of motors mainly consist of two loops the inner loop for current and the outer loop for speed.

### 2.6.3 Torque control mode

Torque control used in PMSM model predicts the voltage required to achieve a desired torque or speed. So by using current and voltage measurements and rotor position in sensor controlled machine. It is possible to estimate the instantaneous rotor or stator flux and output torque demanded values within a fixed sampling time. The calculated voltage is then evaluated to provide pulses to the inverter which drives the motor. The torque control mode is used where precise control of torque is required. It is used in molding industries.

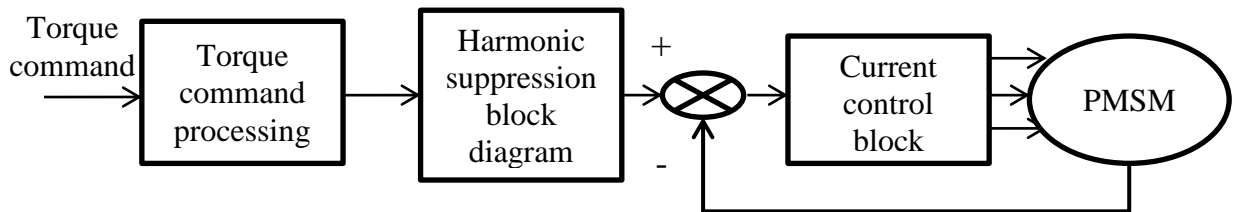


Fig 2.8 Torque control mode

## 2.7 Conclusion

In this chapter the basic model of the drive system, the types of permanent magnet motors, materials used for permanent magnets, the types of current controllers have been briefly discussed. The operation of PMSM in position, speed and torque control mode is also presented.

## Chapter 3

# MATHEMATICAL MODELING OF PMSM DRIVE SYSTEM

### 3.1 Introduction

This chapter deals with the dynamics and detailed modeling of a permanent magnet synchronous motor. Scalar control and Field oriented control of the motor in constant torque and flux-weakening regions are discussed. Closed loop control of the motor is developed using a Intelligent Controller in the speed loop. Design of the speed controller is discussed.

### 3.2 Modeling of PMSM

Detailed modeling of PM motor drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame as shown in figure 3.1. At any time  $t$ , the rotating rotor d-axis makes an angle  $\theta_r$  with the fixed stator phase axis and rotating stator mmf makes an angle  $\alpha$  with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

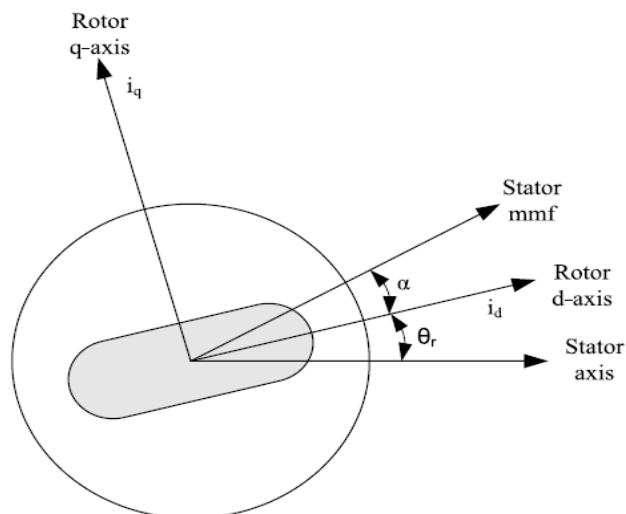


Figure 3.1 diagram showing motor axis

The model of PMSM without damper winding has been modeled on rotor reference frame using the following assumptions:

- (i). Saturation is neglected.
- (ii). The induced EMF is sinusoidal.
- (iii). Eddy currents and hysteresis losses are negligible.
- (iv). There are no field current dynamics.

Voltage equations are given by:

$$v_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \quad (3.1)$$

$$v_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \quad (3.2)$$

Where  $v_q, v_d, i_q, i_d, \lambda_d, \lambda_q$  are q-axis voltage, d-axis voltage, q-axis current, d-axis current, flux linkage of d-axis and flux linkage of q-axis respectively.

Flux linkages are given by:

$$\lambda_q = L_q i_q \quad (3.3)$$

$$\lambda_d = L_d i_d + \lambda_f \quad (3.4)$$

By Substituting equations:

$$v_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_q i_q \quad (3.5)$$

$$v_d = R_s i_d + \rho (L_d i_d + \lambda_f) - \omega_r L_q i_q \quad (3.6)$$

Arranging equations in matrix form

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \quad (3.7)$$

The developed motor torque is given by:

$$T_e = \frac{3}{2} \left( \frac{p}{2} \right) (\lambda_d i_q - \lambda_q i_d) \quad (3.8)$$



Where P is total number of poles.

The mechanical Torque equation is:

$$T_e = T_L + B\omega_m + J \frac{d\omega_m}{dt} \quad (3.9)$$

Where  $T_L$ , B and J are load torque, friction and inertia respectively.

Solving for the rotor mechanical speed form equation:

$$\omega_m = \int \left( \frac{T_e - T_L - B\omega_m}{J} \right) dt \quad (3.10)$$

And

$$\omega_m = \omega_r \left( \frac{2}{P} \right) \quad (3.11)$$

Where  $\omega_m$  and  $\omega_r$  represent electrical speed and rotor speed respectively.

### 3.2.1 Parks Transformation and Dynamic d q Modeling

The dynamic d q modeling is used for the study of motor during transient and steady state. It is done by converting the three phase voltages and currents to dqo variables by using Parks transformation [20].

Converting the phase voltages variables  $v_{abc}$  to  $v_{dq0}$  variables in rotor reference frame the following equations are obtained:

$$\begin{bmatrix} v_q \\ v_d \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin \theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.12)$$

By converting dq-abc

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos \theta_r & \sin \theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} v_q \\ v_d \\ v_0 \end{bmatrix} \quad (3.13)$$

### 3.2.2 Equivalent Circuit of Permanent Magnet Synchronous Motor

Equivalent circuits of the motors are used for analysis and simulation studies on motors. From the d-q modeling of the motor using the stator voltage equations the equivalent circuit of the motor is derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source. The field mmf is derived as  $\lambda_f = L_{dm} i_f$ . Where  $\lambda_f$  and  $i_f$  are field flux linkage and equivalent permanent magnet field current respectively.

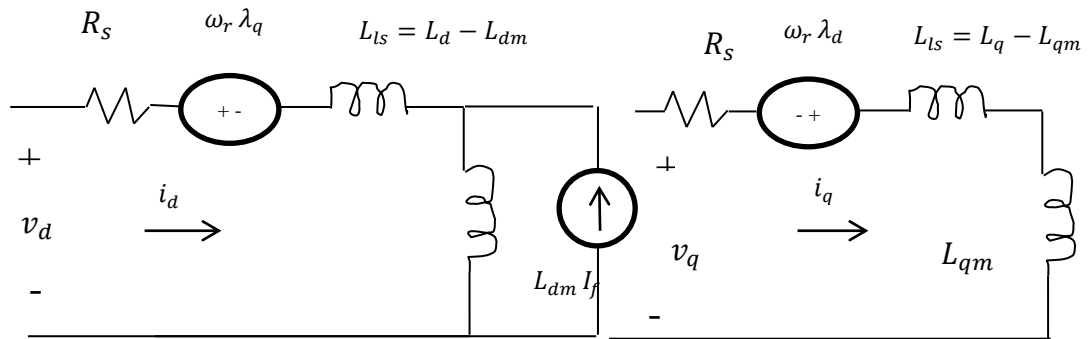


Figure 3.2 Equivalent diagram circuit diagram of PMSM without damper winding.

### 3.3 PM Motor Control

The control of PMSM is possible using two techniques namely:

- (i). Scalar control
- (ii). Vector control

In scalar control amplitude and frequency are controlled. In vector control position of the space vector and amplitude are considered.

The figure 3.3 indicates how the basic control strategies are classified based on variable frequency control.

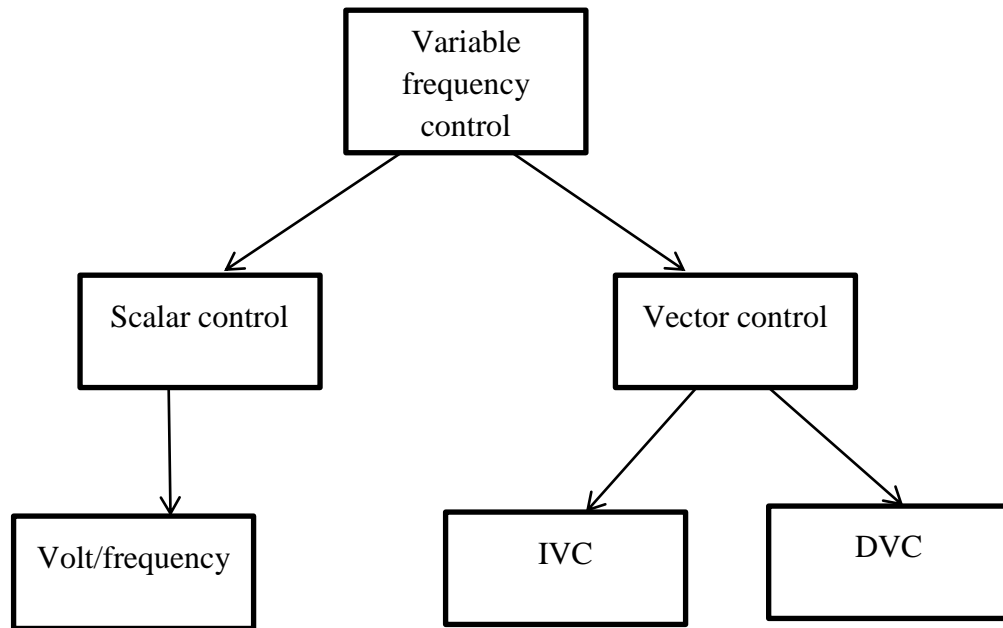


Fig 3.3 Variable frequency control types of AC drives

### 3.3.1 Scalar control

This method is based on varying two parameters simultaneously. The speed can be varied by increasing or decreasing the supply frequency, but this results in change in impedances there by change in current ie: either decreases or increases which eventually effects the torque.it is simple and basic speed control method. The scalar control technique gives good steady state response for ac drive but poor dynamic performance. Moreover this thesis deals with vector control hence more emphasis is laid on explaining vector control and only brief theory about scalar control has been presented.

#### 3.3.1.1 Voltage/frequency control

Voltage/frequency control is one of the most widely used scalar control technique in the motors. The simplicity is coming from the fact that the control is made in open loop scheme and is not using any feedback loop. The open loop control is simple and less costly but accuracy of speed or frequency control is poor. Current and torque are not controlled, instead voltage and frequency are becoming the controlled variables. The principle is based on keeping the stator flux constant at rated value for the motor to

develop rated torque/ampere ratio over entire speed range. A sinusoidal voltage PWM algorithm is implemented to increase the amplitude of fundamental voltage.

Therefore the dynamic performance is poor, with high overshoot. The signal used in feedback loop is of the rotor position which is needed to maintain the synchronism between the rotor and the stator field.

### **3.3.2 Vector control**

The scalar control technique provides good steady state performance but poor dynamic performance for AC Drives. The researchers have found that the main reason for the poor performance in dynamic state is that air gap flux linkages deviate from their set values. The deviation is not only in magnitude but also in phase. These variations in flux linkages result in oscillation in electromagnetic torque which if left unchecked they reflect on speed there by causing oscillations in the speed. This is undesirable in many high performance applications Such as in robotics, process drives, servos where high precision, fast positioning or speed control are required.

Further the air gap flux linkage variations cause change in stator currents which demands high rating converters and inverters. Hence in order to overcome all these disadvantages the research in vector control led to vast advancement in usage of AC Drives.

A vector control ac drive is operated as separately- excited dc drive where it is much simpler because the flux and torque control is done independently. Thereby dependence of torque on flux or vice-versa is nullified. Moreover the dc motor control requires only the control of field or armature current magnitude, providing simplicity not possible with ac machine control. In contrast ac motor drives require a co-ordinated control of stator current magnitudes, frequencies and their phases, making it a complex control. In this case, the stator currents are expressed with reference to the frame co-ordinates which rotates in synchronism either with the stator or rotor mmf vector. The stator currents expressed on these co-ordinates are resolved into two orthogonal components which produce the flux and torque in the motor. The flux component is along the rotor flux linkages which is the field producing current which requires constant

positioning of the field co-ordinates hence this is strategy is also called field-oriented control.

Thus vector control made the ac drives equivalent to dc drives in the independent control of flux and torque and superior to them in their dynamic performance. These developments positioned the ac drives for high-performance applications.

### 3.3.2.1 vector control of PMSM

The vector control is very popular in industrial applications. In vector control the rotor angle  $\theta_r$  is generated through measurement of the rotor position with an encoder/synchronous resolver and converted into necessary digital information for feedback. Some transducers can directly convert the rotor position information into velocity. A vector controller accepts the torque and flux requests and generates the torque and flux-producing components of the stator current phasor.

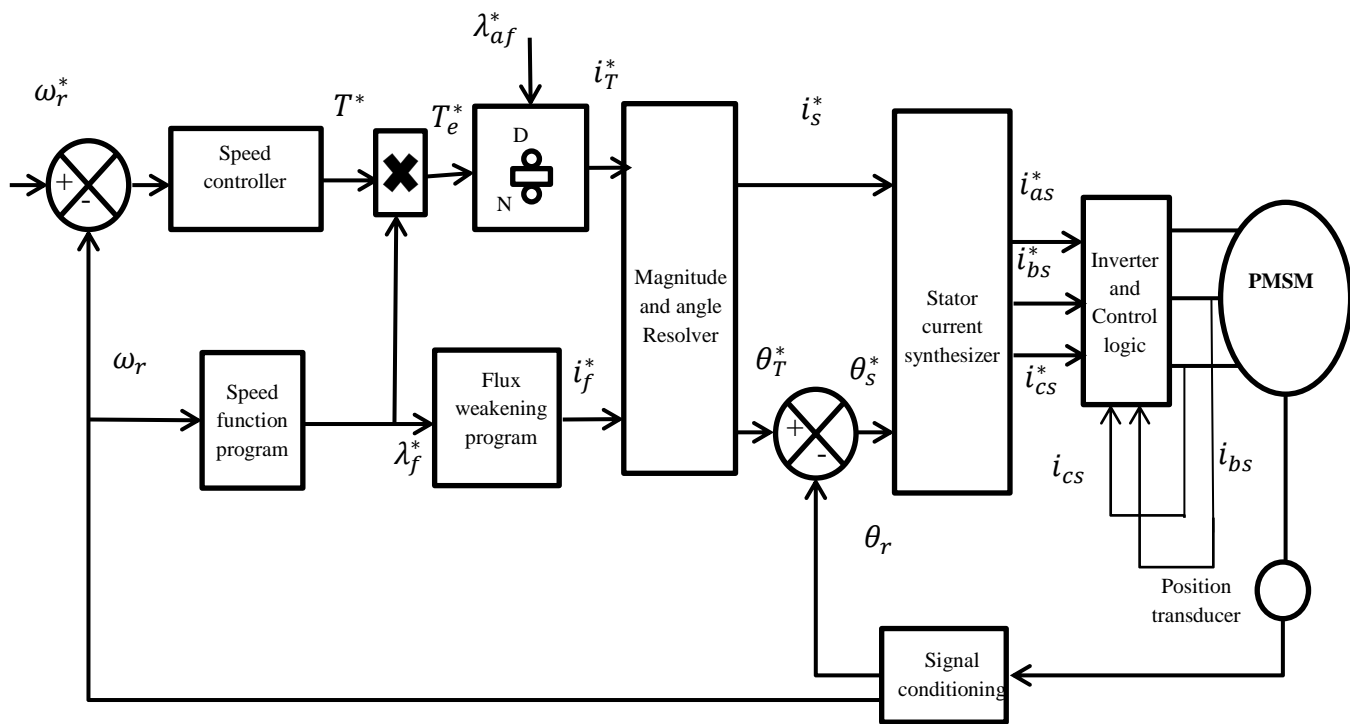


Fig 3.5: vector control scheme of PMSM

Where  $\theta_T^*$  is reference torque angle

The instantaneous position of the stator current phasor command is given by

$$\theta_s^* = \theta_r + \theta_T^* \text{ and } \theta_T^* = \tan^{-1} \left[ \frac{i_T^*}{i_f^*} \right]$$

$\omega_r$  is electrical rotor speed in rad/sec.

### 3.4 Field Oriented Control of PM Motors

The PMSM control is equivalent to that of the dc motor by a decoupling control known as field oriented control or vector control. The vector control separates the torque component of current and flux channels in the motor through its stator excitation.

The vector control of the PM synchronous motor is derived from its dynamic model. Considering the currents as inputs, the three currents are:

$$i_a = I_m (\sin \omega_r t + \alpha) \quad (3.14)$$

$$i_b = I_m \left( \sin \omega_r t + \alpha - \frac{2\pi}{3} \right) \quad (3.15)$$

$$i_c = I_m \left( \sin \omega_r t + \alpha + \frac{2\pi}{3} \right) \quad (3.16)$$

Writing the above equations in matrix form

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\omega_r t + \alpha) \\ \cos\left(\omega_r t + \alpha - \frac{2\pi}{3}\right) \\ \cos\left(\omega_r t + \alpha + \frac{2\pi}{3}\right) \end{bmatrix} I_m \quad (3.17)$$

Where  $\alpha$  is the angle between the rotor field and stator current phasor,  $\omega_r$  is the electrical rotor speed.

The previous currents obtained are the stator currents that must be transformed to the rotor reference frame with the rotor speed  $\omega_r$ , using Park's transformation. The q and d axis currents are constants in the rotor reference frames since  $\alpha$  is a constant for a given load torque. As these constants, they are similar to the armature and field

currents in the separately excited dc machine. The q axis current is distinctly equivalent to the armature current of the dc machine; the d axis current is field current, but not in its entirety. It is only a partial field current; the other part is contributed by the equivalent current source representing the permanent magnet field. For this reason the q axis current is called the torque producing component of the stator current and the d axis current is called the flux producing component of the stator current.

Substituting the above equations we obtain  $i_d$  and  $i_q$  in terms of  $I_m$

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \sin \alpha \\ \cos \alpha \end{bmatrix} I_m \quad (3.18)$$

Where  $I_m$  is peak value of supply current.

Using equations and the electromagnetic torque equation is obtained as given below

$$T_e = \frac{3P}{2} \left[ \frac{1}{2} (L_d - L_q) I_m^2 \sin 2\alpha + \lambda_f I_m \sin \alpha \right] \quad (3.19)$$

Where P and  $\alpha$  are total number of poles and angle between the rotor field and stator current phasor respectively.

The torque- angle control provides a wide variety of control choices in PMSM drive system. Some key control strategies are the following:

1. Constant torque-angle control or zero direct axis current control.
2. Flux-weakening control.

### 3.4.1 Constant Torque-Angle Control

Constant torque-angle control strategy is derived from field oriented control, where the maximum possible torque is desired at all times like the dc motor. This is performed by making the torque producing current  $i_q$  equal to the supply current  $I_m$ . That results in selecting the angle  $\alpha$  to be 90° degrees according to equation (3.18). By making the  $i_d$  current equal to zero the torque equation can be rewritten as:

$$T_e = \frac{3P}{2} \lambda_f i_q \quad (3.20)$$

Assuming that:

$$\text{Where } K_t = \frac{3P}{2} \lambda_f \quad (3.21)$$

The torque is obtained as:

$$T_e = K_t i_q \quad (3.22)$$

Like the dc motor, the torque is dependent of the motor current.

### 3.4.2 Flux-Weakening Control

Flux weakening is the process of reducing the flux in the d axis direction of the motor which results in an increased speed range. The motor drive is operated with rated flux linkages up to a speed where the ratio between the induced emf and stator frequency (V/f) is maintained constant. After the base frequency, the V/f ratio is reduced due to the limit of the inverter dc voltage source which is fixed. The weakening of the field flux is required for operation above the base frequency. This reduces the V/f ratio. This operation results in a reduction of the torque proportional to a change in the frequency and the motor operates in the constant power region [17].

This method changes torque by altering the angle between the stator MMF and the rotor d axis. In the flux weakening region where  $\omega_r > \omega_{rated}$  angle  $\alpha$  is controlled by proper control of  $i_d$  and  $i_q$  for the same value of stator current. Since  $i_q$  is reduced the output torque is also reduced. The angle  $\alpha$  can be obtained as:

$$\alpha = \tan^{-1} \left( \frac{i_q}{i_d} \right) \quad (3.22)$$

The current  $I_m$  related to  $i_d$  and  $i_q$  is given by:

$$I_m = \sqrt{i_d^2 + i_q^2} \quad (3.23)$$

### 3.5 Speed Control of Motor

The speed control of motor is done using different controllers like PI, Fuzzy and Predictive current controllers.

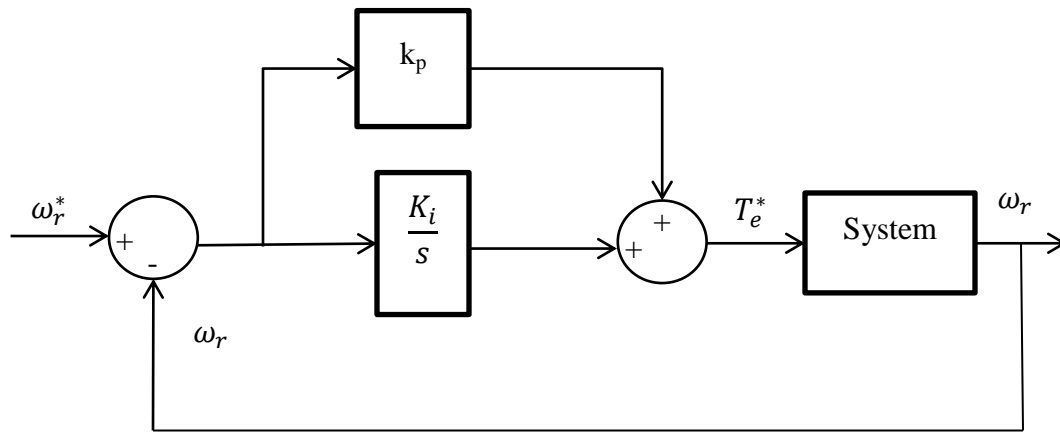
#### 3.5.1 PI controller

Speed controller calculates the difference between the reference speed  $\omega_r^*$  and the actual speed  $\omega_r$  producing an error, which is fed to the PI controller. PI controllers are used



widely for produces an output proportional to the input error and an integration to make the steady state error zero for a step change in the input.

PI controllers are one of the most widely used controllers.it is simple to design and easy to tune. The tuning of PI controllers is done through various methods such as cohen-coon, Tyreus-tuyben and the most famous, regularly used one is Ziegler-nicholas method.



**Figure 3.5 block diagram of PI controller**

### 3.5.2 Fuzzy logic controller

Fuzzy logic is a form of many valued logic or probabilistic logic. It deals with reasoning that is approximate rather than fixed and exact. Compared to traditional binary sets. Where variables may take on true or false value. In fuzzy logic variables may have a truth value that ranges in degree between 0 and1 fuzzy logic has been extended to handle the concept of partial truth where the truth value may range between completely true and completely false. Furthermore when linguistic variables are used these degrees may be managed by specific functions.

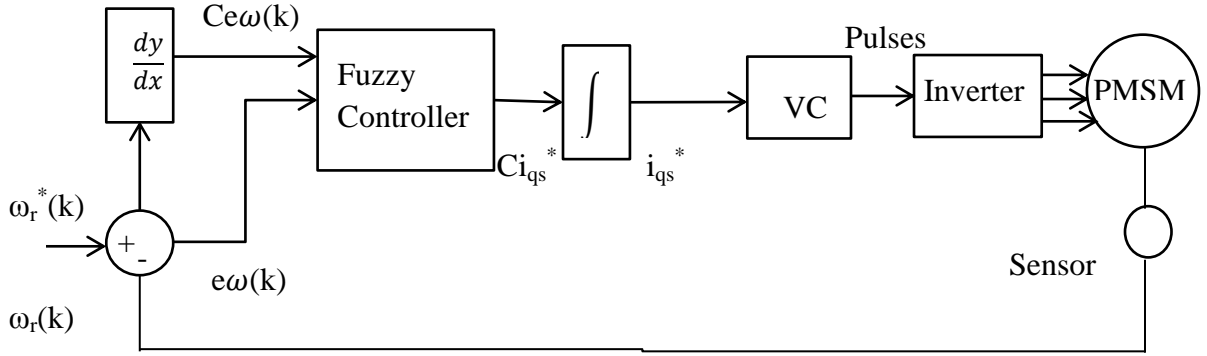


Figure 3.6: fuzzy logic controller block diagram

The design of the fuzzy logic controller starts with assigning the input and output variables. The most significant input variables entering the fuzzy logic speed controller have been selected as the error in speed  $e\omega(k)$  and change of error in speed with respect to time  $ce\omega(k)$ . Two input variables  $e\omega(k)$  and  $ce\omega(k)$  are calculated at every sampling instant as:

$$e(k) = \omega_r^*(k) - \omega_r(k) \quad (3.24)$$

$$ce(k) = e\omega(k) - e\omega(k-1) \quad (3.25)$$

Where  $\omega_r^*(k)$  is the reference speed,  $\omega_r(k)$  is the actual rotor speed and  $e\omega(k-1)$  is the value of error at previous sampling time. The output variable of the fuzzy logic speed controller is the change in command current  $ci_{q_s}^*(k)$ , which is integrated to get the reference command current  $i_{q_s}^*(k)$ , are shown in the following equation.

$$i_{q_s}^*(k) = i_{q_s}^*(k-1) + ci_{q_s}^*(k) \quad (3.26)$$

### 3.5.2.1 Fuzzification

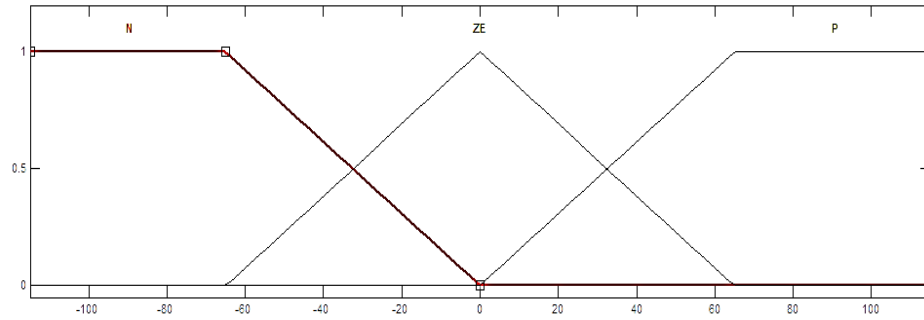
In this stage, the crisp variables of error in speed  $e\omega(k)$  and change of error in speed  $ce\omega(k)$  are converted in to fuzzy variables and respectively. The membership functions associated to the control variables have been chosen with triangular shapes as shown in Fig 3.7. The proposed controller uses following linguistic labels

Negative (N)

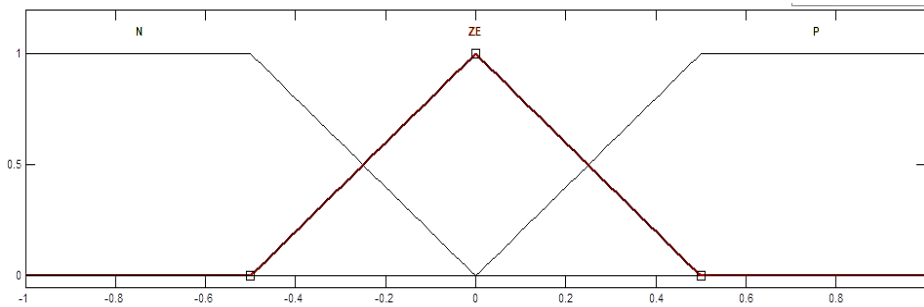
Zero error (ZE)

Positive (P)

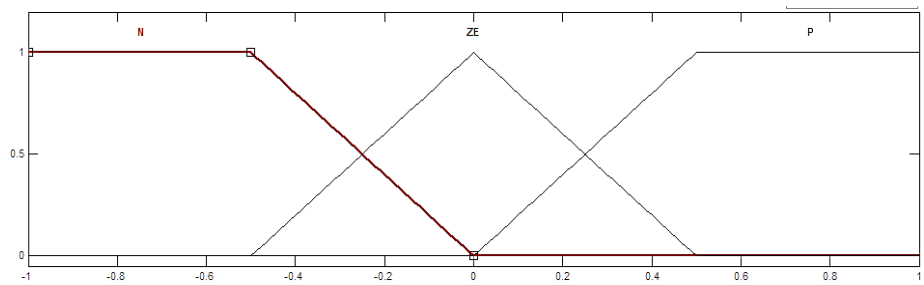
Each fuzzy variable is a member of the subsets with degree of membership varying between 0 and 1.



Input variable 1  $e\omega(k)$



Input variable 2  $ce\omega(k)$



Output variable  $ci_{qs}^*(k)$

Figure 3.7: Membership function representing two input variables and output variable

### 3.5.2.2 Knowledge Base and Inference Stage

Knowledge base involves defining the rules represented as IF-THEN statements governing the relationship between input and output variables in terms of membership functions. In this stage, the variables  $e\omega(k)$  and  $ce\omega(k)$  are processed by an inference engine that executes 9 rules which is shown in Table 3.1. These rules are established using the knowledge of the system behavior. The inference method used is mamdani. For illustration purpose the each rule is expressed in the following way:

IF  $e\omega(k)$  is Negative (N) AND  $ce\omega(k)$  Negative(N) THEN  $ci_{qs}^*(k)$  is Negative(N)

$e\omega(k)$ $ce\omega(k)$	N	ZE	P
N	N	N	ZE
ZE	N	ZE	P
P	ZE	P	P

Table 3.1: fuzzy rule base

### 3.5.2.3 Defuzzification

In this stage a crisp value of the output variable is obtained by using height defuzzification method, in which the centroid of each output membership function for each rule is first evaluated. The final output is then calculated as the average of the individual centroid, weighted by their heights (degree of membership) as follows:

$$ci_{qs}^*(k) = \frac{\sum_{i=0}^n \mu[(ci_{qs}^*)_i](ci_{qs}^*)_i}{\sum_{i=1}^n \mu[(ci_{qs}^*)_i]} \quad (3.27)$$

The reference value of command current  $i_{qs}^*$  that is applied to vector control system is computed by the equation

### 3.5.2.4 TUNING FUZZY LOGIC CONTROLLER

Tuning FLC is most important part of the process. Proper values of gains need to be chosen so that the FLC membership values are properly selected so as to ensure proper functioning of the controller. The FLC shown in Fig. 3.7 can be tuned in a similar way of PI controller where we can find  $K_p$  &  $K_i$  as follows:

$$GCE * GCU = K_p \quad (3.27)$$

$$\frac{GE}{GCE} = \frac{1}{\tau_i} \quad (3.28)$$

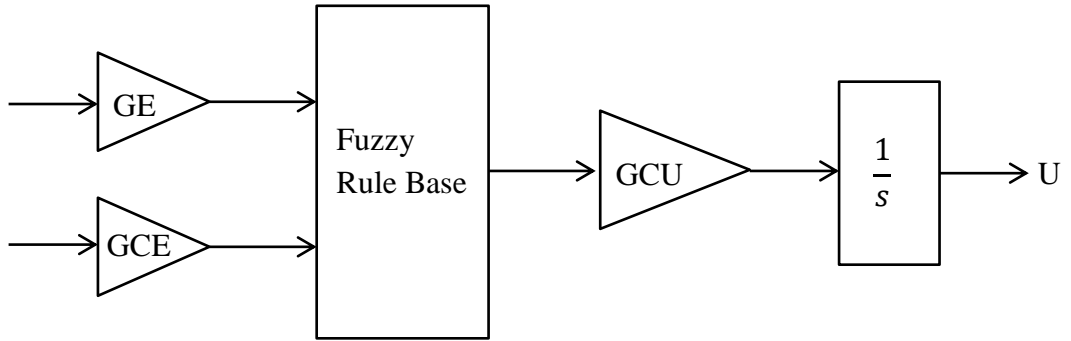


Fig. 3.7 Fuzzy incremental controller

So now like the PI controller we tune the parameters  $GCE, GCU$  &  $GE$  to find the possible values of  $K_p$  &  $K_i$  to best fit the values & provide the best control possible through the fuzzy logic controller.

### 3.5.3 Predictive control

All the physical systems have constraints like physical, safety and performance. Depending upon our requirement these constraints are manipulated and the required output is obtained.

### **3.5.3.1 Difference Between Classical Control and Predictive Control**

#### **Classical control**

1. No knowledge of constraints
2. The operation of the system is not done for optimal results.
3. The desired output can only be achieved if all the constraints are manipulated with utmost accuracy.

#### **Predictive control**

1. The constraints are included in the design of the system.
2. The operation of the system is done for optimal results.
3. The output achieved is much closer to the desired output as the constraints are estimated prematurely.

### **3.5.3.2 PREDICTIVE CURRENT CONTROL**

The direct torque control (DTC) concept has some well-known drawbacks such as variable switching frequency, relatively high torque ripple, and the need for a short sampling time. Several authors have addressed these problems by either applying space vector modulation (SVM) to DTC or recently, using advanced control approaches such as predictive control. The performance of the basic DTC scheme can also be enhanced by other means, such as by using multilevel inverters. The inherent torque ripple of the motor can be reduced by applying advanced optimization techniques.

Predictive control, in which the discrete states of control variables are calculated in advance, has already been successfully applied to PMSM. Various methods based on prediction have also been proposed for surface-mounted permanent-magnet synchronous machines. The implementation of predictive approach called “direct current control” is used in this thesis in direct current control technique the current error is calculated with which sampling time is manipulated and accordingly switching frequency of the inverter there by ripples in current/torque can be minimized.

In direct current control technique the ripples in current/torque can be minimized by finding the current error using certain specific algorithm based on discretization of motor equations the operation of PMSM is done using constant torque angle strategy where  $\alpha=90^\circ$  hence the equations are formulated as follows

$$i_d = 0 \quad (3.29)$$

$$i_q = i_s \quad (3.30)$$

$$\text{Since } \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \sin \alpha \\ \cos \alpha \end{bmatrix} I_m$$

from equation (3.18) in other words d-axis current is considered zero. In order to calculate q-axis reference current  $i_q^*$  following equations are considered.

As already mentioned the equations considered are in discrete state. The change in rotor speed  $\omega_r$  is

$$\frac{d\omega_r}{dt} = \frac{\omega_r(n+1) - \omega_r(n)}{T} \quad (3.31)$$

The subscript (n) represents present state and (n+1) represents next sample and T is duration between two samples. Considering the fact that the synchronous motor has fixed speed hence the motor's next sample state (n+1) as known the desired value of electromagnetic torque  $T_e$  is derived as follows:

$$\omega_r(n+1) = \omega_r^* \quad (3.32)$$

$$T_e^* = B\omega_r + T_m + \frac{J}{P} \left[ \frac{\omega_r^* - \omega_r(n)}{T} \right] \quad (3.33)$$

We know that  $T_e = \frac{3P}{2} \lambda_f i_q$  from equation (3.20) now using equations (3.20),(3.32),(3.33) .

$i_q^*$  can be obtained as:

$$i_q^* = \frac{2}{3 * P * \lambda_f} \left[ B\omega_r + T_m + \frac{J}{P} \left[ \frac{\omega_r^* - \omega_r(n)}{T} \right] \right] \quad (3.34)$$

Using equations (3.5) and (3.6), since  $\mathbf{p}$  is derivative operator

$$v_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + L_q \frac{di_q}{dt} \quad (3.35)$$

$$v_d = R_s i_d + \frac{d}{dt} (L_d i_d + \lambda_f) - \omega_r L_q i_q \quad (3.36)$$

By writing the above equations in discrete time

$$v_d = R_s i_d(n) + L_d \frac{i_d(n+1) - i_d(n)}{T} - L_q \omega_r i_q(n) \quad (3.37)$$

$$v_q = R_s i_q(n) + L_d \omega_r i_d(n) + \lambda_f \omega_r + L_q \frac{i_q(n+1) - i_q(n)}{T} \quad (3.38)$$

From the above equations the estimated values  $i_d$  and  $i_q$  at next sample  $i_d(n+1), i_q(n+1)$  can be obtained as:

$$i_d(n+1) = i_d(n) + \frac{T}{L_d} [v_d - R_s i_d(n) + L_q \omega_r i_q(n)] \quad (3.39)$$

$$i_q(n+1) = i_q(n) + \frac{T}{L_q} [v_q - R_s i_q(n) - L_d \omega_r i_d(n) - \omega_r \lambda_f] \quad (3.40)$$

Now in order to reduce the current and torque ripples the estimated d-q axis currents

$i_d(n+1), i_q(n+1)$  must track the respective reference currents accurately. Hence the error in currents is defined as:

$$\Delta i_d = i_d^* - i_d(n+1) \quad (3.41)$$

$$\Delta i_q = i_q^* - i_q(n+1) \quad (3.42)$$

Thus using these currents  $\Delta i_d$  and  $\Delta i_q$  the switching of the inverter is done in order to get minimum ripples in torque/current.

### 3.6 Conclusion

In this chapter dynamics of PMSM is discussed, The vector control has been stated along with the control strategies which are widely used in control of PMSM. The tuning of PI and Fuzzy logic controllers has been explained briefly. The predictive control which is one of the new technique has also been stated.

Further in the next chapter the results of PMSM control using PI, Fuzzy and Predictive Current Controllers have been shown.



## **Chapter 4**

### **Simulation results**

#### **4.1 General**

This chapter presents simulation results for vector controlled Permanent magnet synchronous motor (PMSM). Study of dynamic performance of electric motor drives needs the proper selection of a simulation tool. SIMULINK is a toolbox of the MATLAB program. It is a program for simulating dynamic systems. The simulation environment of Simulink has a high flexibility and expandability which allows the possibility of development of a set of functions for a detailed analysis of the electrical drive. Using Simulink model the actual prototype of vector controlled PMSM drive have been studied. The simulation of vector controlled drive of PMSM using different controllers have been discussed in the previous chapters and results of the discussion are summarized in this chapter.

#### **4.2 MATLAB MODELS**

The MATLAB models of Vector Controlled Drive For PMSM using different speed controllers have been shown in fig 4.1. It consists of 3-phase 1HP, 300V, 3750 rpm Permanent Magnet Synchronous Motor (PMSM), a 3-phase voltage source Inverter and Hysteresis Current Controller. The speed controller used in simulation of the drive system as shown in fig.4.1 (a) is conventional PI controller, fig.4.1 (b) shows Fuzzy Logic Controller and fig.4.1 (c) shows Predictive Current Controller.

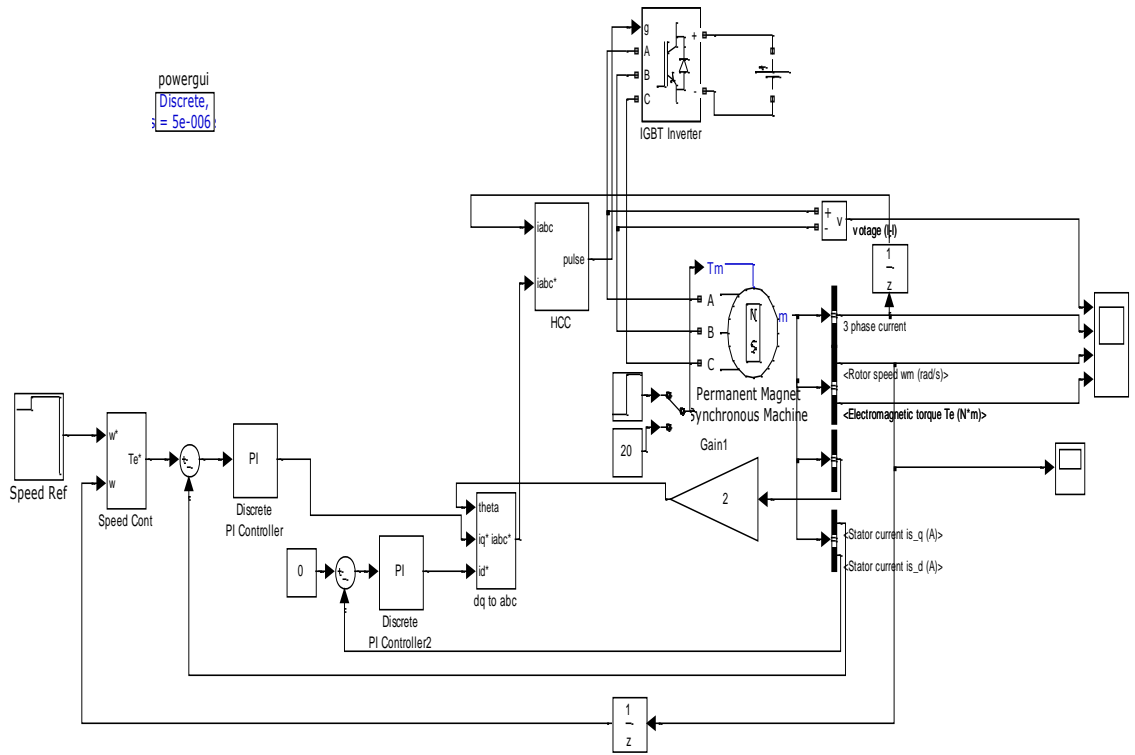


Fig. 4.1 (a) Simulink model of VCPMSM using PI controller

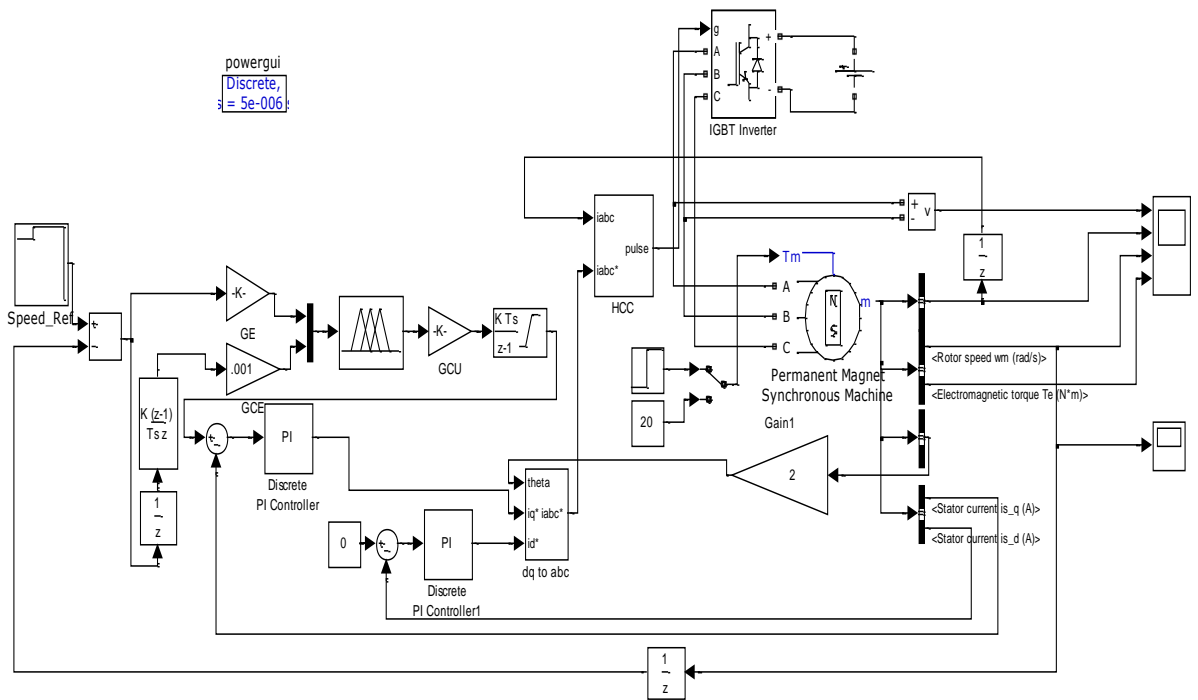


Fig.4.1 (b) Simulink model of VCPMSM using FUZZY controller

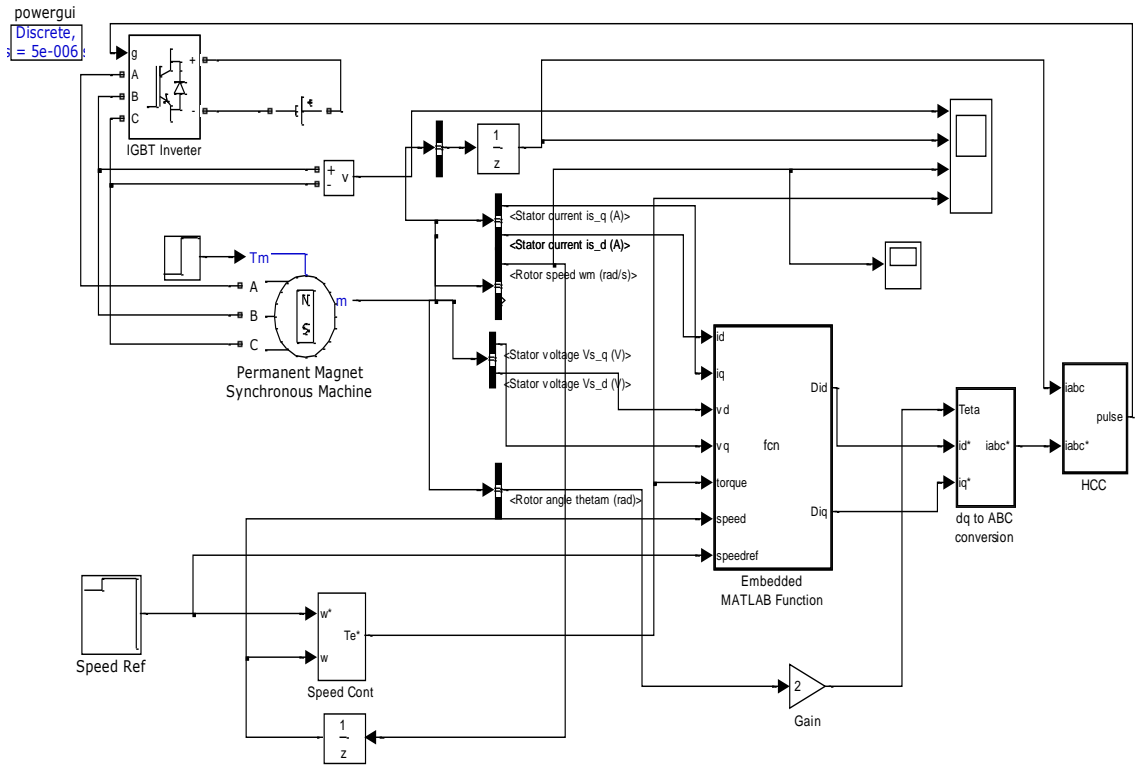


Fig. 4.1 (c) Simulink model of VCPMSM using PREDICTIVE CONTROL

### 4.3 Performance Analysis of Vector Controlled PMSM using PI controller

The dynamic behavior of vector controlled Drive for PMSM, 3-phase 1 HP, 300 V, 3750 rpm (392 rad/sec), PMSM was studied initially through a conventional PI speed controller, where the actual speed ( $\omega_r$ ) of the motor is sensed through in built sensor. The actual speed is compared with reference speed  $\omega_r^*$  and the difference is processed by PI controller. During simulation the initial speed of motor is set at 120 (rad/sec) it reaches to steady state level in about 0.01 sec where the initial load is zero. Now when the speed is changed to 180 (rad/sec) at 0.05 sec it reaches to steady state which is less than fraction of a second. The initial starting current is quite high and when it reaches to steady state at 0.04 sec the current is 1amp. At 0.1 sec load of 0.5 N-M is applied it is observed that there is a slight decrease in the speed, but the PI controller regulates the speed so that it reaches to desired value faster. The motor speed to reaches to steady state level at 0.12 seconds. The steady state current after achieving 180 (rad/sec) at 0.12 sec is 3.75 amp. At

0.15 sec the speed in reverse motoring is set at 180 (rad/sec) it reaches to steady state at about

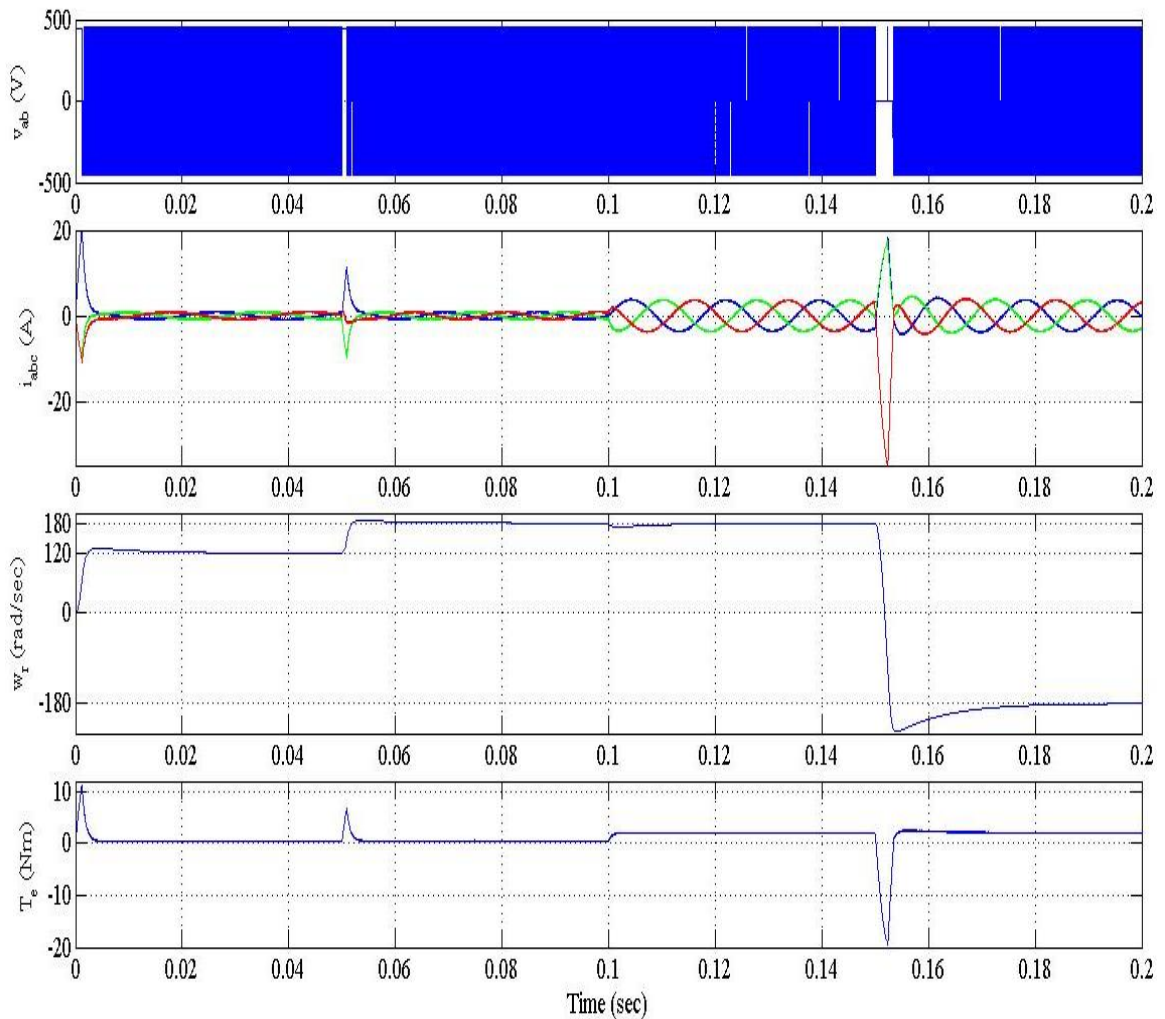


Fig 4.2: Performance analysis of VCPMSM using PI for (a) no load (b) load applied at  $t=0.1$  sec

0.18 sec. Fig 4.2 shows the line voltage  $V_{ab}$ , the line current ( $i_a$ ,  $i_b$  and  $i_c$ ), the speed ( $\omega_r$ ) and the electromagnetic torque ( $T_e$ ) developed by the motor for the above operating conditions.

#### 4.4 Performance Analysis of Vector Controlled PMSM using Fuzzy Logic controller

The dynamic performance of Vector Controlled PMSM is analyzed using a Fuzzy Logic Controller also. The FLC speed controller is developed using rule base which has already been discussed in the previous chapter. The simulation result is shown in Fig. 4.3. The operating conditions are kept the same as that for the simulation using PI controller to analyze the performance between the control schemes under same operating conditions.

The dynamic behavior of Vector controlled Drive for PMSM, 3-phase 1HP, 300 V, 3750 rpm (392 rad/sec) is presented in fig 4.3. In simulation the desired speed of the motor is set at 120 rad/sec under no load then the motor reaches steady state condition ie:120 rad/sec much faster than the PI controller that to with smooth transition. The initial current is quite high but less compared to that of PI controller and as motor reaches to steady state condition the current settles at 0.9 amps at 120 rad/sec.

When the speed is set to change from 120 rad/sec to 180 rad/sec at 0.05 sec the transition is comparatively smooth from 120 rad/sec to 180 rad/sec. When a load 0.5 N-M load is applied at 0.1sec it is observed that there is a variation in speed for initial few sec and there after the motor acquires the steady state at 0.103 sec which is faster response compared to that of PI controller. There is change in current properties as well it is 3.75 amp as speed settles at 180 rad/sec.

At 0.15 sec the speed in reverse motoring is set at 180 rad/sec it reaches to desired value at about 0.16 sec with smooth transition. Fig 4.3 shows line voltage  $V_{ab}$ , the line current ( $i_a$ ,  $i_b$  and  $i_c$ ), the speed ( $\omega_r$ ) and the electromagnetic torque ( $T_e$ ) developed by the motor for the above operating conditions.

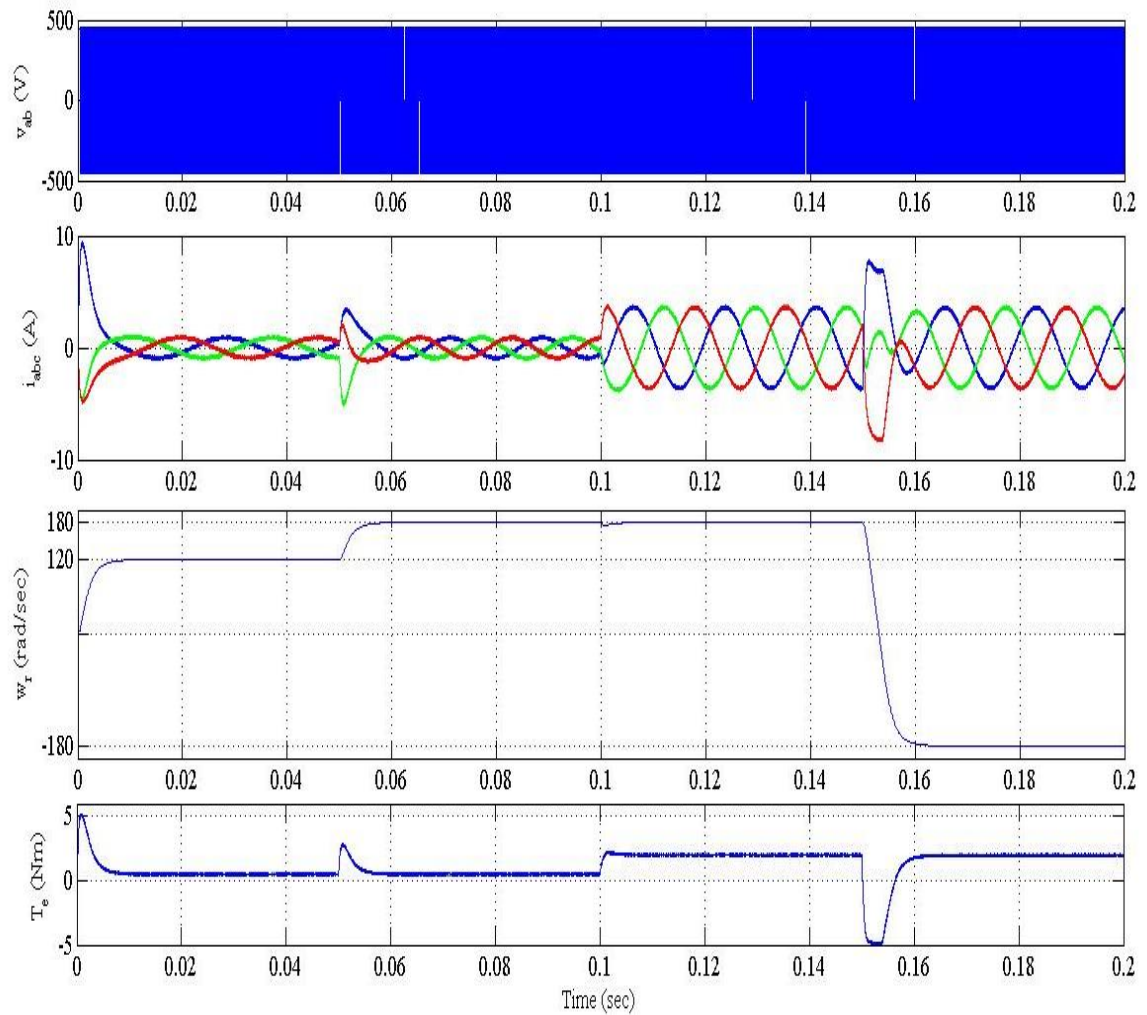


Fig 4.3: Performance analysis of VCPMSM using FLC controller for (a) no load (b) load applied at  $t=0.1$  sec

#### 4.5 Performance analysis of VCPMSM using Predictive current controller

Predictive control is advanced technique compared to PI and fuzzy. An algorithm written to estimate the next state currents with which one can estimate the error in currents by comparing it with previous state. Embedded MATLAB C function is used to write the algorithm. The main aim using this method is to reduce the ripples in current and torque.

The motor with same rating and operating conditions is used in predictive control which has been used previously in PI and fuzzy controlling techniques. A PMSM of 3-

phase, 300 V, 1HP, 3750 rpm (392 rad/sec) with initial speed at 120 rad/sec is operated with PCC and it is observed in fig 4.4 that it attains the steady state speed in 0.04 sec.

Then the speed is changed from 120 rad/sec to 180 rad/sec at 0.05 sec the motor reaches to steady state with smooth transition with minimum delay in time. When the load is changed at 0.1 sec from 0 NM to 0.5 N-M the current increases and speed are regulated. At 0.15 sec the speed in reverse motoring is set at 180 rad/sec it reaches to desired value at about 0.2 sec.

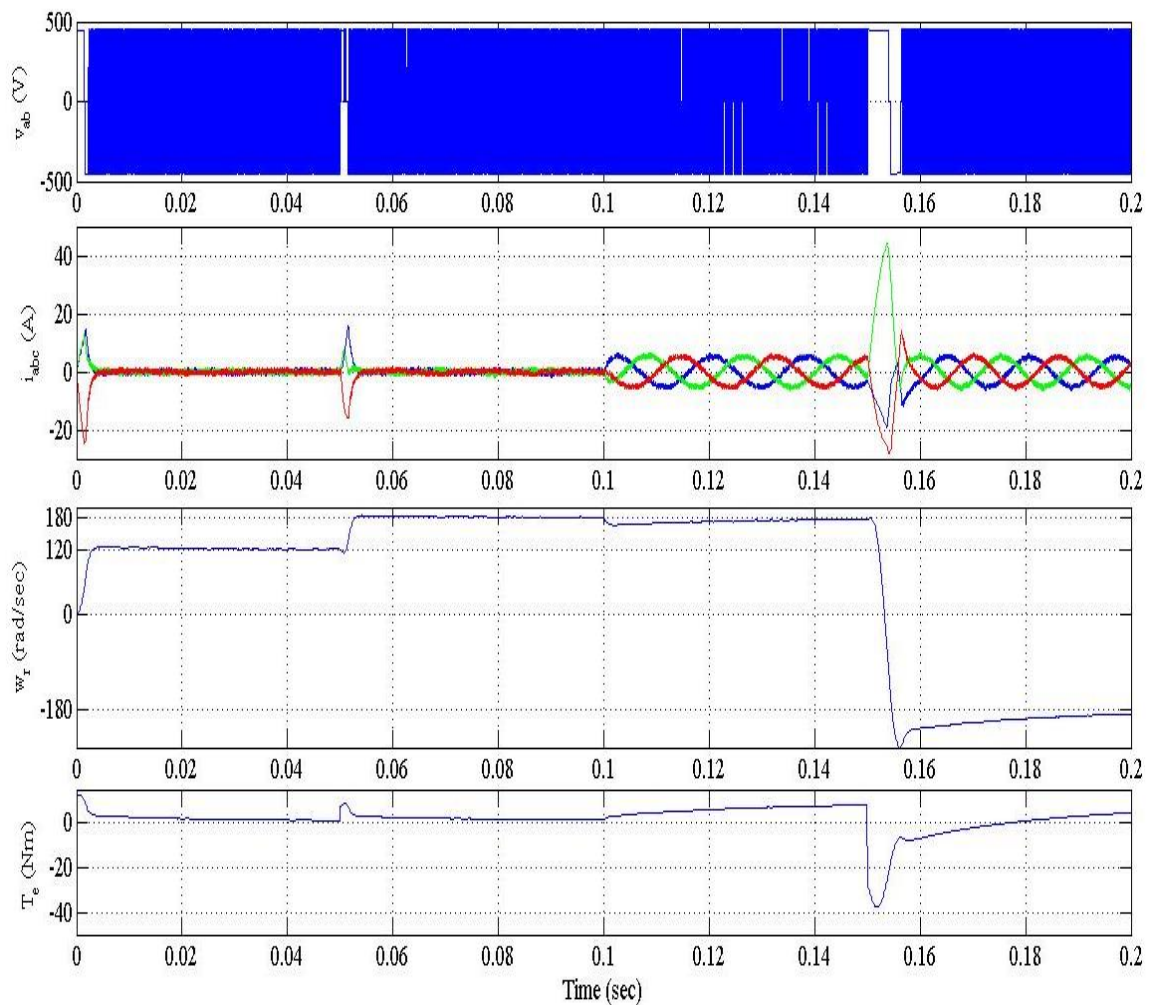


Fig 4.4: Performance analysis of VCPMSM using PCC for (a) no load (b) load applied at  $t=0.1$  sec

#### 4.6 Comparison of VCPMSM using PI, FUZZY and Predictive Current Controller

A comparison of PMSM dynamic performance is made with three controllers for desired reference speed. From fig 4.5 it is observed that initial speed 120 rad/sec has been attained by the three control techniques at different points but fuzzy logic controller has the smooth transition phase from 0 to 120 rad/sec. Similar changes in behaviour is noticed when the speed is changed from 120 rad/sec to 180 rad/sec which is the desired speed at 0.05 sec. Similarly during change in load condition at 0.1 sec it has minimum deviation from the desired speed or final value of speed 180 rad/sec. Which can be clearly observed.

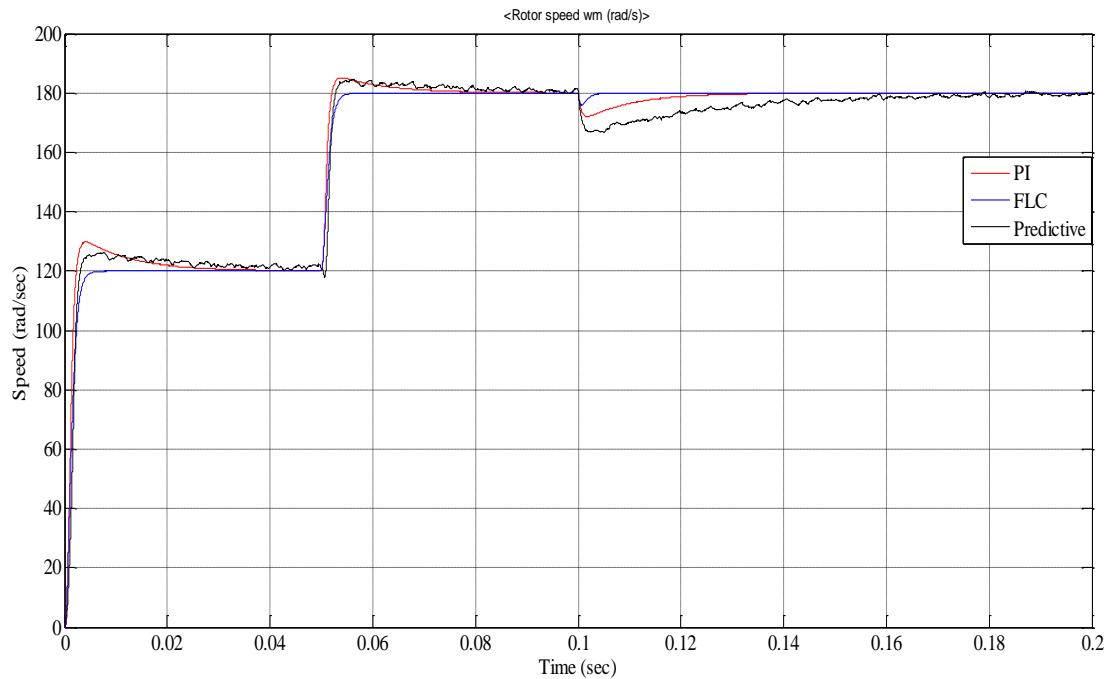


Fig 4.5: Comparison of Speed deviation in PI, Fuzzy and predictive current Controllers

Predictive current controller (PCC) is supposed to reduce ripples in current and torque which depends on the speed and vice-versa. The Fuzzy logic controller has better performance compared to PI.



#### 4.6.1 Comparison of PI, FLC and PCC under various operating conditions

The comparison between the PI, FLC and PCC under different operating conditions. Considering steady state error, rise time, settling time and steady state current. The results of PI, FLC and PCC shown in fig 4.2, fig 4.3 and fig 4.4 respectively are used for analysis.

**Table 4.1 Operation under no load for  $\omega_r = 120\text{rps}$**

	PI	FLC	PCC
Reference speed	120 rps	120 rps	120 rps
Rise time	.002sec	.0044 sec	.00243
Settling time	.025sec	.014 sec	.0245
Steady state error	0.33 %	0.08 %	1.9 %
Steady state current	1A	1 A	1.1 A

**Table 4.2 Operation under no load for  $\omega_r = 180\text{rps}$**

	PI	FLC	PCC
Reference speed	120 to 180 rps	120 to 180 rps	120 to 180 rps
Rise time	.002 sec	.00541 sec	.002 sec
Settling time	.0138 sec	.01272	.01366
Steady state error	0.27 %	0 %	1.6 %
Steady state current	1 A	1 A	1.1 A

**Table 4.3 Operation under load of 0.5 NM applied at 0.1 sec for  $\omega_r = 180\text{ rps}$**

	PI	FLC	PCC
Reference speed	180 rps	180 rps	180 rps
Settling time	.028 sec	.0133 sec	.05 sec
Steady state error	0.27 %	0 %	1.33 %
Steady state current	3.8 A	3.73 A	6.3 A

#### **4.7 Conclusion**

The performance of PMSM in vector controlled mode is analyzed using PI, FLC and PCC and a comparison of response are presented in this chapter.

## Chapter 5

# Conclusion and Future Scope of Work

### 5.1 Main Conclusions

A detailed Simulink model for a PMSM drive system with field oriented control has been developed with different types of controllers like PI, Fuzzy and Predictive current controller. The simulations of drive system with different controllers was carried out in MATLAB/Simulink. This enables us to understand the behaviour of the PMSM drive system under different operating conditions.

Simulink has been chosen from several simulation tools because its flexibility in working with analog and digital devices. Mathematical models are easily incorporated in the simulation and the presence of numerous tool boxes and support guides simplifies the simulation of large system. Simulink is capable of showing real time results with reduced simulation time and debugging. The Simulink models can be reproduced in real time operation.

In the present simulation measurement of currents and voltages in each part of the system is possible. The FLC speed controller eliminates the transients during sudden change in load as compared to that of PI controller. The response of FLC is faster than PI controller. The predictive current controller with proper algorithm eliminates the ripples in current and toques.

The error between the speed command and the actual speed is also greatly reduced. Hysteresis current controllers have a variable switching frequency that depends of the hysteresis band and if the bandwidth is very small it may affect the device switching capability. However, the simulation with hysteresis current controller allows faster simulations with reduced time and computational resources. A speed controller has been designed successfully for closed loop operation of the PMSM drive system so that the motor runs at the commanded or reference speed.

### 5.2 Future Scope of Work

The implementation of additional control techniques like unity power factor control, constant mutual air gap flux linkages control, optimum torque per ampere control and

sensorless control can be taken up for detail simulation and performance calculation of PMSM drive systems. A neural network which is far more advanced than fuzzy and predictive controllers can also be explored for further improvement in the dynamics of the drive. Extensive research is being carried out in neural networks and predictive control techniques. A real-time implementation of the proposed controllers using DS1104 controller may be implemented and the overall behaviour of the drives in its full range of operation could be analyzed.

## References

- [1]. V.B. Honsinger," The fields and parameters of interior type ac permanent magnet machines". IEEE-Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 4, pp. 867 – 875, 1982.
- [2]. M.A. Rahman, T.A. Little G.R. Slemon,"Analytical models for interior-type permanent magnet synchronous motor".IEEE transactions on magnetics, vol. mag-21, no. 5, pp. 1741- 1743, 1985.
- [3]. T. Sebastian, G. Slemon, and M. Rahman, "Modelling of permanent magnet synchronous motors," IEEE Transactions on Magnetics, vol. 22, pp. 1069-1071,1986.
- [4]. T. M. Jahns, G. B.Kliman, and T. W. Neumann, "Interior Permanent-Magnet Synchronous Motors for Adjustable-Speed Drives," IEEE Transactions on Industrial Applications, vol. IA-22, pp. 738-746, 1986.
- [5]. P. Pillay and R. Krishnan, "Modeling of permanent magnet motor drives," IEEE Transactions on Industrial Electronics, vol. 35, pp. 537-541, 1988.
- [6]. P. Pillay and R. Krishnan, "Modeling, simulation, and analysis of permanent-magnet motor drives. I. The permanent-magnet synchronous motor drive," IEEE Transactions on Industry Applications, vol. 25, pp. 265-273,1989
- [7]. Pragasen Pillay,Ramu krishnan. "Control Characteristics and Speed Controller Design for a High Performance Permanent MagnetSynchronous Motor Drive",IEEE Transactions on power electronics vol. 5 no,pp.151-158, 1990.
- [8]. S. Morimoto, Y. Tong, Y. Takeda, and T. Hirasu, "Loss minimization control of permanent magnet synchronous motor drives," IEEE Transactions on Industrial Electronics, vol. 41, pp. 511-517, 1994.
- [9]. M. A. El-Sharkawi,El-Sayed,"High Performance Drive of DC Brushless Motors Using Neural Network".IEEE Transactions on Energy Conversion. Vol. 9, No. 2, pp.317-322, 1994.
- [10]. P. Zhou, M. A. Rahman,"Field Circuit Analysis of Permanent Magnet Synchronous Motors".IEEE transactions on magnetics, vol. 30, no. 4,pp.1350-1359, 1994.

- [11]. A. H. Wijenayake and P. B. Schmidt, "Modeling and analysis of permanent magnet synchronous motor by taking saturation and core loss into account," 1997.
- [12]. K. Jang-Mok and S. Seung-Ki, "Speed control of interior permanent magnet synchronous motor drive for the flux weakening operation," *Industry Applications, IEEE Transactions on*, vol. 33, pp. 43-48, 1997.
- [13]. L. Zhong, M. F. Rahman, "Analysis of Direct Torque Control in Permanent Magnet Synchronous Motor Drives", *IEEE transactions on power electronics*, vol. 12, no. 3, pp.528-536, 1997.
- [14]. C. Ong, *Dynamic Simulation of Electric Machinery using Matlab/Simulink: Prentice Hall*, 1998.
- [15]. M.A Rahman, M.A. Hoque, "On-line Adaptive Artificial Neural Network Based Vector Control of Permanent Magnet Synchronous Motors", *IEEE Transactions on Energy Conversion*, Vol. 13, No. 4, pp.311-318, 1998.
- [16]. Kyeong-Hwa Kim, In-Cheol Baik, Gun-Woo Moon, and Myung-Joong Youn, "A Current Control for a Permanent Magnet Synchronous Motor with a Simple Disturbance Estimation Scheme". *IEEE transactions on control systems technology*, vol. 7, no. 5, pp.630-633, 1999.
- [17]. B. Cui, J. Zhou, and Z. Ren, "Modeling and simulation of permanent magnet synchronous motor drives," 2001.
- [18]. R krishnan, *Electric motor drives modeling, analysis and control*. Pearson Education 2000.
- [19]. Bor-Jehng Kang and Chang-Ming Liaw, "A Robust Hysteresis Current-Controlled PWM Inverter for Linear PMSM Driven Magnetic Suspended Positioning System". *IEEE transactions on industrial electronics*, vol. 48, no. 5, pp.956-967, 2001.
- [20]. B. K. Bose, *Modern power electronics and AC drives*: Prentice Hall, 2002.
- [21]. M. Nasir Uddin, Tawfik S. Radwan, M. Azizur Rahman, "Performance of Interior Permanent Magnet Motor Drive Over Wide Speed Range". *IEEE transactions on energy conversion*, vol. 17, no. 1, pp.79-84, 2002.

- [22]. Hyung-Tae Moon, Hyun-Soo Kim, "A Discrete-Time Predictive Current Control for PMSM", IEEE transactions on power electronics, vol. 18, no. 1, pp.464-472, 2003.
- [23]. Naomitsu Urasaki, Tomonobu Senjyu, "Investigation of Influences of Various Losses on Electromagnetic Torque for Surface-Mounted Permanent Magnet Synchronous Motors", IEEE transactions on power electronics, vol. 18, no. 1, pp.131-139, 2003.
- [24]. Yang Yi, D. Mahinda Vilathgamuwa, M. Azizur Rahman, "Implementation of an Artificial-Neural-Network-Based Real-Time Adaptive Controller for an Interior Permanent-Magnet Motor Drive". IEEE transactions on industry applications, vol. 39, no. 1, pp.96-104, 2003.
- [25]. Jawad Faiz, S. Hossein Mohseni-Zonoozi, "a novel technique for estimation and control of stator flux of a salient-pole PMSM in dtc method based on mtpf", IEEE transactions on industrial electronics, vol. 50, no. 2, pp.262-271, 2003.
- [26]. Jung-Ik Ha, "Sensorless Rotor Position Estimation of an Interior Permanent-Magnet Motor From Initial States". IEEE transactions on industry applications, vol. 39, no. 3, pp.761-767, 2003.
- [27]. M. Nasir Uddin, M. A. Abido, "Development and Implementation of a Hybrid Intelligent Controller for Interior Permanent-Magnet Synchronous Motor Drives", IEEE transactions on industry applications, vol. 40, no. 1, pp.68-76, 2004.
- [28]. Gilead Tadmor, "Control of a Combined GTO/IGBT Drive System for Low Torque Ripple in a Large Permanent Magnet Synchronous Motor". IEEE transactions on control systems technology, vol. 12, no. 1, pp.21-35, 2004.
- [29]. Khalid I. Saleh, Osama A. Mohammed, Mohammed A. Badr, "Field-Oriented Vector Control of Synchronous Motors With Additional Field Winding". IEEE transactions on energy conversion, vol. 19, no. 1, pp.95-101, 2004.
- [30]. Jian-Xin Xu, S. K. Panda, Ya-Jun Pan, Tong Heng Lee and B. H. Lam, "A Modular Control Scheme for PMSM Speed Control With Pulsating Torque Minimization". IEEE transactions on industrial electronics, vol. 51, no. 3, pp.526-536, 2004.

- [31]. M. Nasir Uddin, M. A. Abido, "Real-Time Performance Evaluation of a Genetic-Algorithm-Based Fuzzy Logic Controller for IPM Motor Drives. IEEE transactions on industry applications, vol. 41, no. 1, pp.246-251, 2005.
- [32]. Todd D. Batzel, Kwang Y. Lee, "Electric Propulsion With Sensorless Permanent Magnet Synchronous Motor: Implementation and Performance", IEEE transactions on energy conversion, vol. 20, no. 3, pp.575-583, 2005.
- [33]. Mario Pacas, Jürgen Weber, "Predictive Direct Torque Control for the PM Synchronous Machine", IEEE transactions on industrial electronics, vol. 52, no. 5, pp.1350-1356, 2005.
- [34]. Mohamed Boussak, "Implementation and Experimental Investigation of Sensorless Speed Control With Initial Rotor Position Estimation for Interior Permanent Magnet Synchronous Motor Drive". IEEE transactions on power electronics, vol. 20, no. 6, 2005.
- [35]. Paolo Mattavelli, Luca Tubiana and Mauro Zigliotto, "Torque-Ripple Reduction in PM Synchronous Motor Drives Using Repetitive Current Control". IEEE transactions on power electronics, vol. 20, no. 6, pp.1423-1431, 2005.
- [36]. M. Nasir Uddin, Tawfik S. Radwan, and M. Azizur Rahman, "Fuzzy-Logic-Controller-Based Cost-Effective Four-Switch Three-Phase Inverter-Fed IPM Synchronous Motor Drive System". IEEE transactions on industry applications, vol. 42, no.1, pp.21-29, 2006.
- [37]. Mongkol Konghirun and Longya Xu, "A Fast Transient-Current Control Strategy in Sensorless Vector-Controlled Permanent Magnet Synchronous Motor". IEEE transactions on power electronics, vol. 21, no. 5, pp.1508-1512, 2006.
- [38]. Yasser Abdel-Rady Ibrahim Mohamed, "Design and Implementation of a Robust Current-Control Scheme for a PMSM Vector Drive With a Simple Adaptive Disturbance Observer", IEEE transactions on industrial electronics, vol. 54, no. 4, pp.1981-1988, 2007.
- [39]. Mohamed Rashed, Peter F. A. MacConnell, A. Fraser Stronach, and Paul Acarnley, "Sensorless Indirect-Rotor-Field-Orientation Speed Control of a Permanent-Magnet Synchronous Motor With Stator-Resistance Estimation". IEEE transactions on industrial electronics, vol. 54, no. 3, pp.1664-1675, 2007.



- [40]. Jae-Sung Yu, Sang-Hoon Kim, Byoung-Kuk Lee, Chung-Yuen Won, and Jin Hur, "Fuzzy-Logic-Based Vector Control Scheme for Permanent-Magnet Synchronous Motors in Elevator Drive Applications", IEEE transactions on industrial electronics, vol. 54, no. 4, pp.2190-2200, 2007.
- [41]. Yasser Abdel-Rady Ibrahim Mohamed, "A Newly Designed Instantaneous-Torque Control of Direct-Drive PMSM Servo Actuator With Improved Torque Estimation and Control Characteristics". IEEE transactions on industrial electronics, vol. 54, no. 5, pp.2864-2873, 2007.
- [42]. Ying-Shieh Kung, Ming-Hung Tsai, "FPGA-Based Speed Control IC for PMSM Drive With Adaptive Fuzzy Control". IEEE transactions on power electronics, vol. 22, no. 6, pp.2476-2486, 2007.
- [43]. Yasser Abdel-Rady Ibrahim Mohamed, "Direct instantaneous torque control in-direct drive permanent magnet synchronous motors—a new approach", IEEE transactions on energy conversion, vol. 22, no. 4, pp.829-838, 2007.
- [44]. Roozbeh Molavi, Khoshnam Shojaee, "Optimal Vector Control of Permanent Magnet Synchronous Motor". 2nd IEEE International Conference on Power and Energy (PECon 08) 2008.
- [45]. Joerg Weigold and Michael Braun, "Predictive Current Control Using Identification of Current Ripple", IEEE transactions on industrial electronics, vol. 55, no. 12, pp.4343-4346, 2008.
- [46]. Florent Morel, Lin-Shi and Cyril Buttay, "A Comparative Study of Predictive Current Control Schemes for a Permanent-Magnet Synchronous Machine Drive". IEEE transactions on industrial electronics, vol. 56, no. 7, pp.2715-2728, 2009.
- [47]. Mitja Nemec, Klemen Drobnic, "Direct Current Control of a Synchronous Machine in Field Coordinates", IEEE transactions on industrial electronics, vol. 56, no. 10, pp.4052-4061, 2009.
- [48]. M. Nasir Uddin, Ronald S. Rebeiro, "Online Efficiency Optimization of a Fuzzy-Logic-Controller-Based IPMSM Drive", IEEE transactions on industry applications, vol. 47, no. 2, pp.1043-1050, 2011.

- [49]. Hao Zhu, Xi Xiao and Yongdong Li, "Torque Ripple Reduction of the Torque Predictive Control Scheme for Permanent-Magnet Synchronous Motors", IEEE transactions on industrial electronics, vol. 59, no.2, pp.871-877, 2012.
- [50]. Radoslaw Nalepa, Teresa Orłowska-Kowalska, "Optimum Trajectory Control of the Current Vector of a Nonsalient-Pole PMSM in the Field-Weakening Region". IEEE transactions on industrial electronics, vol. 59, no. 7, pp.2867-2876, 2012.