Sudan University of Science and Technology

College of Engineering

Electrical Engineering Department

Field Oriented Control Applied to Permanent Magnet Synchronous Machine

التحكم في المجال الموجه المطبق علي الماكينة التزامنية ذات المغناطيس الدائم

A Project Submitted in Partial Fulfillment for Requirements of the Degree of B.Sc. (Honor) in Electrical Engineering

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الآية

بسم الله الرحمن الرحيم

قال تعالي :

(" يَا أَيُّهَا الَّذِينَ آمَنُوا إِذَا قِيلَ لَكُمْ تَفَسَّحُوا فِي الْمَجَالِسِ فَافْسَحُوا يَفْسَحِ اللَّهُ لَكُمْ وَإِذَا قِيلَ انْشُزُوا فَانْشُزُوا يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ").

سوره المجادله (11)

DEDICATION

To our parents the reason of what we became today, Thanks for your great patience support and Continuous care. To our friends and colleagues whom are always with us and force source to go forward. We also dedicate this study to our teachers to give us moral support. And finally big thanks to Sudan university of science and technology.

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ABSTRACT

The thesis deals with the detailed modeling of a permanent magnet synchronous motor drive system in Simulink. Field oriented control is used for the operation of the drive. The simulation includes all realistic components of the system. This enables the calculation of currents, voltages, torque and speed in different parts of the inverter and motor under transient and steady conditions. The losses in different parts are calculated, facilitating the design of the inverter. A closed loop control system with a Proportional Integral (PI) controller in the speed loop has been designed to operate in constant torque and flux weakening regions. Implementation has been done in Simulink. A comparative study of hysteresis and Pulse Width Modulation (PWM) control schemes associated with current controllers has been made in terms of harmonic spectrum and total harmonic distortion. Simulation results are given for two speeds of operation, one below rated and another above rated speed.

المستخلص

عند دراسة نظام التحكم والتشغيل في السرعة للماكينات التزامنية ذات المغنطة الدائمه وتصميم نظام المحاكاة بواسطة برنامج الماتلاب تم التحكم في السرعه بواسطة التحكم في تيارات المجال للعضو الثابت والتي كانت تعطي استاجه ضعيفه لاداء السرعه .

اجريت الدراسة على منظومة معينة تدار بواسطة ماكينة تزامنية ذات اقطاب مغنطة دائمة وتم اختيار سرعة معينة كمرجع يتم مقارنة السرعة المتولده معها حتى يتم الحصول على السرعه المطلوبة .

واظهرت النتائج حركية منتظمة استجابة جيدة واداء مستقر للمنظومه وذلك بالنسبة للعزم والسرعة وتيارات العضو الثابت

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LIST OF ABBREVIATIONS

PM	Permeant Magnet
PI	Proportional Integral
PMSM	Permeant Magnet Synchronous Machine
SVPWM	Space Vector Pulse Width Modulation
FOC	Field-Oriented Control
BLDC	Brushless DC Motors
BJTs	Bipolar Junction Transistors
MOSFETs	MOS Field Effect Transistors
IGBTs	Insulated Gate Bipolar Transistors
GTOs	Gate Turn Off Thyristors
CSI	Current Source Inverters
VSI	Voltage Source Inverters
THD	Total Harmonic Distortion
DSP	Digital Signal Processor
SVM	Space Vector Modulation
FFT	Fast Fourier Transform

LIST OF SYMPOLES

θ	Angle in electrical degrees or radians
θm	Mechanical angle
P	Poles
T_{mech}	Mechanical torque
T_{load}	Load torque
T_{losses}	Mechanical loss torque
P_{mech}	Mechanical power
w_{syn}	Synchronous speed
θ_m	Angle between phasors E_a and I_a.
P_{out}	Output power
I_m	maximum line current
N	Speed
V_{dc}	Source voltage
R_a	Armature resistance
L_d	D-axis inductance
L_q	Q-axis inductance
J	Motor inertia
B	Viscous damping coefficient
λ	PM flux
P	Number of poles
R_c	Stator resistance
I_{max}	Maximum current
I_{rms}	Rms current
T_d	Delay time
Tr	Rise time

M_p	Maximum overshoot
ω_{ref}	Reference speed
ω_r	Rotor electrical speed
Ki	Integral value
Kp	Proportional value
ω_m	Mechanical speed
T	Transformation matrix
f_c	Cutoff frequency

CHAPTER ONE

INTRODUCTION

1.1 General concepts

Permanent magnet motor drives have been a topic of interest for the last twenty years. Different authors have carried out modeling and simulation of such drives.

Permanent magnet (PM) synchronous motors are widely used in low and mid power applications such as computer peripheral equipment’s, robotics, adjustable speed drives and electric vehicles.

The growth in the market of PM motor drives has demanded the need of simulation tools capable of handling motor drive simulations. Simulations have helped the process of developing new systems including motor drives, by reducing cost and time. Simulation tools have the capabilities of performing dynamic simulations of motor drives in a visual environment so as to facilitate the development of new systems.

In this work, the simulation of a field oriented controlled PM motor drive system is developed using Simulink. The simulation circuit will include all realistic components of the drive system.

This enables the calculation of currents and voltages in different parts of the inverter and motor under transient and steady conditions. The losses in different parts can be calculated facilitating the design of the inverter. A closed loop control system with a PI controller in the speed loop has been designed to operate in constant torque and flux weakening regions. Implementation has been done in Simulink. A SVPWM control schemes associated Simulation results are given for the rated speed. [1]

1.2 Problem statement

Vector controlled PMSM drive provides better dynamic response and lesser torque ripples, and necessitates only a constant switching frequency. With the advent of the vector control methods, permanent magnet synchronous motor can be operated like separately excited dc motor high performance application. The complexity of conventional Proportional plus integral (PI) controller has low speed control performance such as high overshoot and less response time.

1.3 Objectives

The main objective of the project is to describe a comprehensive analysis on the principle of operation, design considerations and control algorithms of a PMSM drives speed control system, in order to improved speed control performance of PMSM such as low overshoot, fast response time, low torque and current ripple.

1.4 Methodology

First thing is modeling of permanent magnet synchronous machine, using PI controller for speed and current, using Park transformation for current, using space vector pulse with modulation to generate current pulse, use inverter to convert the source voltage, use MATLAB simulation to present a block drive o the system, calculating the PI constant and select data to work with, the last thing is analysis simulation results.

1.5 Outlines

Chapter one discussed the background and general idea of the proposed project. Besides that, the objectives and methodology are explained. Also we define the problem statement.

Chapter two discovered the reviews which includes the principles of Field Oriented control technique implemented in controlling PMSM drive. Some basis

Space Vector Pulse Width Modulation (SVPWM) theory and the brief reviews of Proportional integral controller and Inverter.

Chapter three shows the models of the system, methodology, and steps of each design stage. The details of the topology are discussed in this chapter with the operations of the system.

Chapter four presents the various results are shown and discussed from the simulation results and analyzed the compensation performance of the system. The simulation results of the systems performance have been observed.

Chapter five states the conclusions or outcome simulation results of the systems performance have been observed of this project.

CHAPTER TWO

PERMENANT MAGNET

SYNCHRONOUS MACHINES EQUIPMENT

2.1 Introduction

In this chapter deals the main equipment use to drive the permanent synchronous machine, inverter (universal bridge), PI controller and space vector pulse modulation (SVPWM).

2.2 Synchronous machine

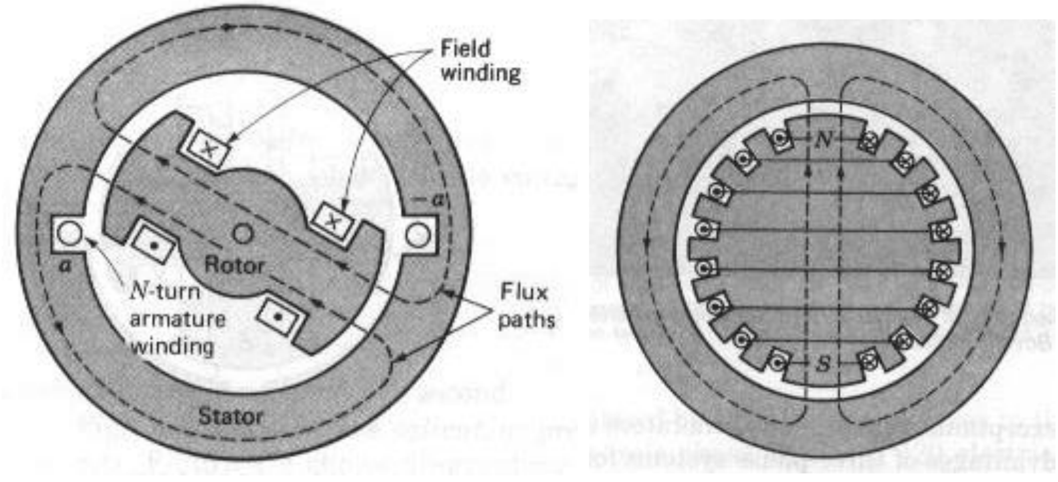
A synchronous machine is an AC rotating machine whose speed under steady state condition is proportional to the frequency of the current in its armature. The magnetic field created by the armature currents rotates at the same speed as that created by the field current on the rotor, which is rotating at the synchronous speed, and a steady torque result. Synchronous machines are commonly used as generators especially for large power systems, such as turbine generators and hydroelectric generators in the grid power supply. Because the rotor speed is proportional to the frequency of excitation, synchronous motors can be used in situations where constant speed drive is required. Since the reactive power generated by a synchronous machine can be adjusted by controlling the magnitude of the rotor field current, unloaded synchronous machines are also often installed in power systems solely for power factor correction or for control of reactive kVA flow. Such machines, known as synchronous condensers, may be more economical in the large sizes than static capacitors. [2]

2.2.1 Synchronous machine structures

Here we mention the main structure :

2.2.1.1 Stator and rotor

The armature winding of a conventional synchronous machine is almost invariably on the stator and is usually a three-phase winding. The field winding is usually on the rotor and excited by dc current, or permanent magnets. The dc power supply required for excitation usually is supplied through a dc generator known as exciter, which is often mounted on the same shaft as the synchronous machine. Various excitation systems using ac exciter and solid-state rectifiers are used with large turbine generators. There are two types of rotor structures: round or cylindrical rotor and salient pole rotor as illustrated schematically in the diagram below. Generally, round rotor structure is used for high speed synchronous machines, such as steam turbine generators, while salient pole structure is used for low speed applications, such as hydroelectric generators. The pictures below show the stator and rotor of a hydroelectric generator and the rotor of a turbine generator. [3]



(a) (b)

Figure 2.1: Schematic illustration of synchronous machines of (a) round or cylindrical rotor and (b) salient rotor structures

2.2.1.2 Angle in electrical and mechanical units

Consider a synchronous machine with two magnetic poles. The idealized radial distribution of the air gap flux density is sinusoidal along the air gap. When the rotor rotates for one revolution, the induced emf, which is also sinusoidal, varies for one cycle as illustrated by the waveforms in the diagram below. If we measure the rotor position by physical or mechanical degrees or radians and the phase angles of the flux density and emf by electrical degrees or radians, in this case, it is ready to see that the angle measured in mechanical degrees or radians is equal to that measured in electrical degrees or radians, i.e.

$$\theta = \theta_m \qquad (2.1)$$

where θ is the angle in electrical degrees or radians and θm the mechanical angle.

A great many synchronous machines have more than two poles. As a specific example, we consider a four-pole machine. As the rotor rotates for one revolution ($\theta m=2\pi$), the emf varies for two cycles

($\theta = 4\pi$), and hence:

$$\theta = 2\theta_m \qquad (2.2)$$

For a general case, if a machine has P poles, the relationship between the electrical and mechanical units of an angle can be readily deduced as

$$\theta = \frac{P}{2}\theta_m \qquad (2.3)$$

2.2.1.3 Distributed three phase windings

The stator of a synchronous machine consists of a laminated electrical steel core and a three-phase winding. below shows a stator lamination of a synchronous machine that has a number of uniformly distributed slots. Coils are to be laid in these slots and connected in such a way that the current in each phase winding would produce a magnetic field in the air gap around the stator periphery as closely as possible the ideal sinusoidal distribution is a picture of a coil.

2.2.2 Synchronous machine operated as a motor

First we need to define these quantities :

2.2.2.1 Electromagnetic power and torque

When a synchronous machine is operated as a motor to drive a mechanical load, in steady state, the mechanical torque of the motor should balance the load torque and the mechanical loss torque due to friction and windage, that is

$$T_{mech} = T_{load} + T_{losses} \tag{2.4}$$

Multiplying the synchronous speed to both sides of the torque equation, we have the power balance equation as

$$P_{mech} = P_{load} + P_{losses} \tag{2.5}$$

where $P_{mech}=T*\omega_{syn}$ the electromagnetic power of the motor,

$$P_{load} = T_{load} * \omega_{syn} \tag{2.6}$$

is the mechanical power delivered to the mechanical load, and

$$P_{loss} = T_{loss} * \omega_{syn} \tag{2.7}$$

the mechanical power loss of the system. Similar to the case of a generator, the electromagnetic power is the amount of power being converted from the electrical into the mechanical power. That is

$$P_{elect} = T * \omega_{syn} = 3*E_a * I_a * \cos\varphi \tag{2.8}$$

where φ is the angle between phasors E_a and I_a.

2.3 Permanent magnet synchronous machines

The development of high-quality permanent magnet materials into commercial production has encouraged several manufacturers to launch various permanent magnet synchronous machines (PMSM) into the market.

Permanent magnet synchronous machines have been applied to servo drives for a long time already, and nowadays, there are quite large permanent magnet synchronous machines also in industrial uses. In wind mill generators.

Permanent magnet synchronous motors (PMSM) are typically used for high-performance and high-efficiency motor drives. High-performance motor control is characterized by smooth rotation over the entire speed range of the motor, full torque control at zero speed, and fast acceleration and deceleration. To achieve such control, vector control techniques are used for PM synchronous motors. The vector control techniques are usually also referred to as field-oriented control (FOC). [4]

2.3.1 Construction of permanent magnet synchronous motor (PMSM)

Permanent Magnet Synchronous Motor, PMSM is a kind of synchronous motor in which permanent magnet is used as rotor to create field poles. No field winding is wound on the rotor.

The basic construction of PMSM is same as that of synchronous motor. The only difference lies with the rotor. Unlike synchronous motor, there is no filed winding on the rotor of PMSM. Field poles are created by using permanent magnet. These Permanent magnets are made up of high permeability and high coercivity materials like Samarium-Cobalt and Neodium-Iron-Boron. Neodium-Iron-Boron is mostly used due to its ease of availability and cost effectiveness. Theses permanent magnets are mounted on the rotor core. [4]

2.3.2 Classification of permanent magnet motors

We have two classification :

2.3.2.1 Direction of field flux

PM motors are broadly classified by the direction of the field flux. The first field flux classification is radial field motor meaning that the flux is along the radius of the motor. The second is axial field motor meaning that the flux is perpendicular to the radius of the motor.

Radial field flux is most commonly used in motors and axial field flux have become a topic of interest for study and used in a few applications. [3]

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 winding.

2.3.3 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 . 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 Ld = Lq .

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 radically 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. [4]

Figure (2.2) shows the placement of the magnet.

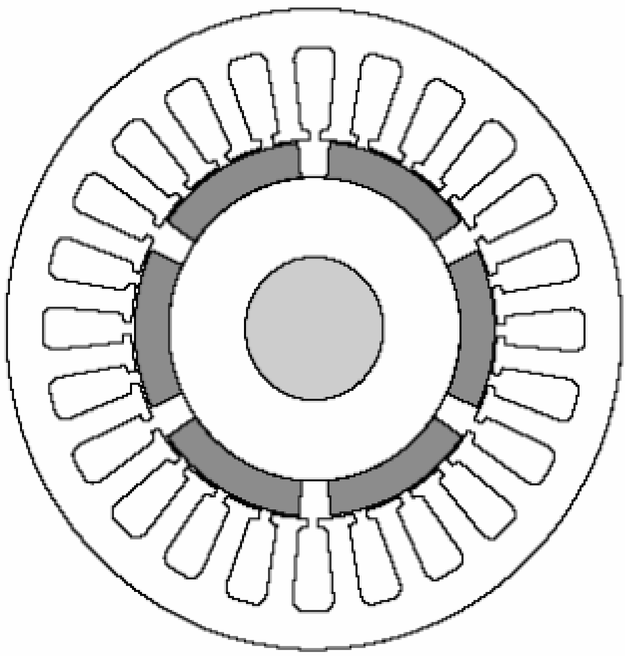


Figure 2.2: Surface permanent magnet motor

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 (Lq > Ld)

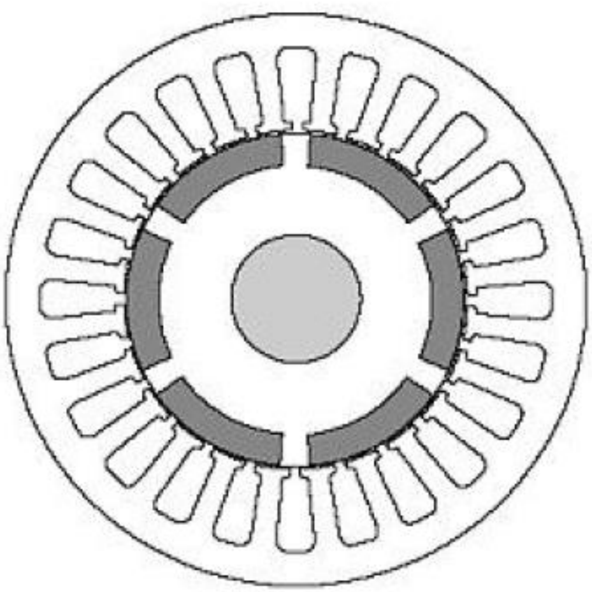


Figure 2.3: Interior permanent magnet motor

2.3.4 Working principle of permanent magnet Synchronous motor (PMSM)

The working principle of permanent magnet synchronous motor is same as that of synchronous motor. When three phase winding of stator is energized from 3 phase supply, rotating magnetic field is set up in the air gap. At synchronous speed, the rotor field poles locks with the rotating magnetic field to produce torque and hence rotor continues to rotate.

As we know that synchronous motors are not self-starting, PMSM needs to be started somehow. Since there is no winding on the rotor, induction windings for starting is not applicable for such motors and therefore variable frequency power supply for this purpose.

2.3.5 PMSM configurations and machine parameters

The characteristics of a permanent magnet machine are highly dependent on the rotor structure. The rotor can be implemented in various ways. When employing the modern permanent magnet materials, the rotor can be constructed even completely without iron. In that case, the rotor frame is constructed for instance of aluminum, onto which the shaped permanent magnets are glued so that the sinusoidal flux density distribution is achieved in the air gap of the machine. An ironless rotor structure wastes permanent magnet material, since the magnetic circuit closes through air in the rotor side. Therefore, a thin steel rim, to which the magnets are attached, the rim can be either a laminated structure, in which case the eddy current losses of the rotor remain very low, or a thin steel tube; however, in this case, there is a danger that the rotor warms up excessively due to the effect of the time harmonics of the stator.

The inductances of a surface-magnet machine are very low, and therefore, a high switching frequency is required of a voltage source inverter in order for the currents of the machine to behave normally. The configuration is applied for instance to servo motors, of which a minimum inertia is required. The direct and quadrature inductance of the machine are in this case approximately equal, and the machine is thus a non-salient pole construction. [4]

2.4 Inverter

Voltage Source Inverters are devices that convert a DC voltage to 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.

Figure 2.4: shows a voltage source inverter. The AC voltage frequency can be variable or constant depending on the application.

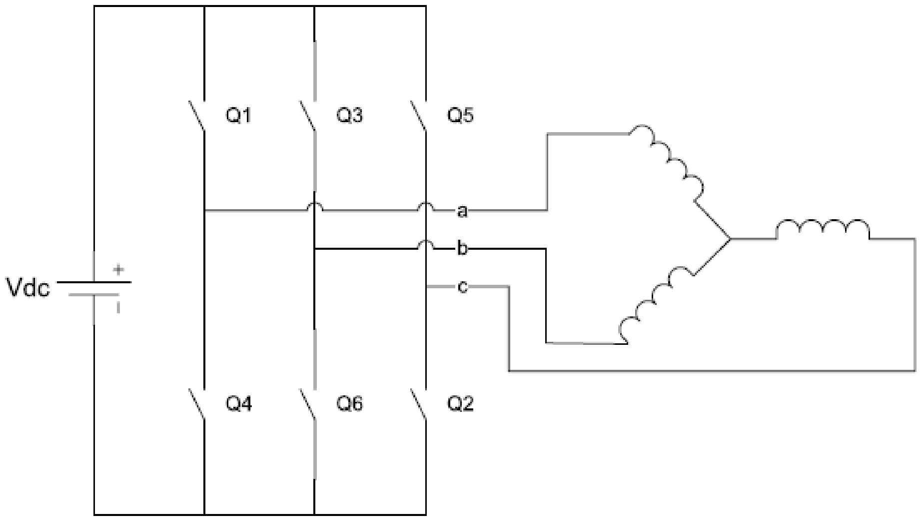


Figure 2.4: Voltage source inverter connected to a motor

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, 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. Inverters with antiparallel diodes.

2.4.1 IGBTs

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. The symbolic representation and the equivalent circuit of an IGBT are shown in figure 2.5:

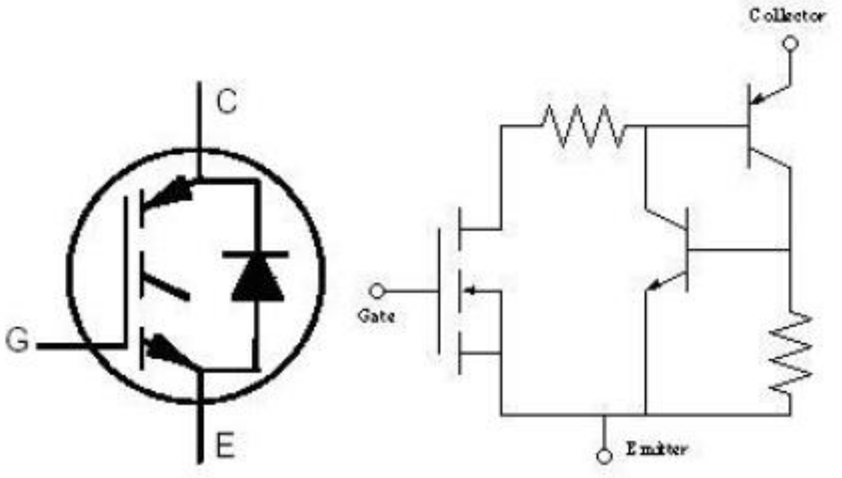


Figure 2.5: IGBT Symbol and equivalent circuit

2.4.2 Current controlled inverter

The motor is fed form 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 efficacy of the drive.

2.5 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 command signals for the AC machine currents. The basic reason for the selection of current as the controlled variable is the same as for the DC machine; the stator dynamics (effects of stator resistance, stator inductance, and induced EMF) are eliminated. Thus, to the extent that the current regulator functions as an ideal current supply, the order of the system under control is reduced and the complexity of the controller can be significantly simplified.

Current regulators for AC drives are complex because an AC current regulator must control both the amplitude and phase of the stator current. The AC drive current regulator forms the inner loop of the overall motion controller. As such, it must have the widest bandwidth in the system and must, by necessity, have zero or nearly zero steady-state error.

Both current source inverters (CSI) and voltage source inverters (VSI) can be operated in controlled current modes. The current source inverter is a "natural" current supply and can readily be adapted to controlled current operation. The voltage source inverter requires more complexity in the current regulator but offers much higher bandwidth and elimination of current harmonics as compared to the CSI and is almost exclusively used for motion control applications.

Current controllers can be classified into two groups, hysteresis and PWM current controllers. Both types are discussed below. [5]

2.5.1 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 desire switching frequency and is compared with error of the controlled signal. The error signal comes from the sum of the reference signal generated in the controller and the negative of the actual motor current. The comparison will result in a voltage control signal that goes to the gates of the voltage source inverter to generate the desire 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 2.6.

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. The nature of the controlled output current consists of a reproduction of the reference current with high-frequency PWM ripple superimposed. [6]

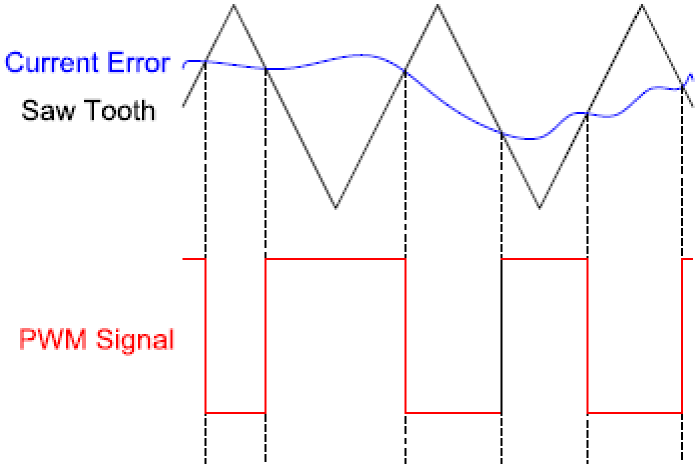


Figure 2.6: PWM current controller

2.6 Space Vector pulse width modulation

Multilevel inverters generate sinusoidal voltages from discrete voltage levels, and pulse width modulation (PWM) strategies accomplish this task of generating sinusoids of variable voltage and frequency. Modulation methods for Hybrid Multilevel Inverter can be classified according to the switching frequency methods. Many different PWM methods have been developed to achieve the following: Wide linear modulation range, less switching loss, reduced Total Harmonic Distortion (THD) in the spectrum of switching waveform: and easy implementation and less computation time.

The most widely used techniques for implementing the pulse with modulation (PWM) strategy for multilevel inverters are Sinusoidal PWM (SPWM) and space vector PWM (SVPWM). The SVPWM is considered as a better technique of PWM implementation as it has advantages over SPWM in terms of good utilization of dc bus voltage, reduced switching frequency and low current ripple. SVPWM is considered a better technique of PWM implementation, as it provides the following advantages,

(i) Better fundamental output voltage.

(ii) Useful in improving harmonic performance and reducing THD.

(iii) Extreme simplicity and its easy and direct hardware implementation in a Digital Signal Processor (DSP).

(iv) SVPWM can be efficiently executed in a few microseconds, achieving similar results compared with other PWM methods.

a space vector is defined in a two-dimensional (2-D) plane and a SVM is performed in the 2-D plane. Furthermore, a three dimensional (3-D) space vector has been defined in this chapter for cascaded H-bridge multilevel inverter. All the existing space vector modulation schemes are implemented in a two-dimensional, and are therefore unable to deal with the zero-sequence component caused by unbalanced load. Complexity and computational cost of traditional SVPWM technique increase with the number of levels of the inverter as most of the space vector modulation algorithms proposed in the literature involve trigonometric function calculations or look-up tables. Previous works on three-dimensional space vector modulation algorithms for diode-clamped inverter. However, unequal dc sources cannot be applied to diode-clamped inverter. Meanwhile, the first 3-D space vector modulation for cascaded H-bridge inverter, which is capable of dealing with zero-sequence component caused by unbalanced load. [6]

2.7 Proportional-Integral controller converters

PI control is becoming more popular because of its ability to maintain exact set point. This chapter aims at establishing the design and implementation of the conventional PI controllers at various operating points of the buck and boost converter. Simulation is done by using MATLAB and the controller is subjected to various disturbances of input voltage and load changes.

2.7.1 PI control mode

Proportional-Integral controller mode results from the combination of the proportional and the integral mode. Certain advantages of both control actions can be obtained from this mode. This mode is also called as the proportional plus reset action controller.

The proportional gain, by design, also changes the net integration mode gain, but the integration gain, can be independently adjusted. It is understood that the proportional offset occurred, when a load change required a new nominal controller output, and this could not be provided except by a fixed error from the set point. In the present mode, the integral function provides the required new controller output, thereby allowing the error to be zero after a load change. The integral feature effectively provides a ‘reset’ of the zero error output, after the load change occurs. At time t1 a load change occurs, that produces the error. The accommodation of the new load condition requires a new controller output. The controller output is provided through a sum of proportional plus integral action that finally leaves the error at zero.

The proportional part is obviously just an image of the error. [7]

2.7.2 Characteristics of the PI mode

- When the error is zero, the controller output is fixed at the value that the integral term had, when the error reduced to zero.

- If the error is not zero, the proportional term contributes a correction and the integral term begins to increase or decrease the accumulated value depending on the sign of the error and its direct or reverse direction. The integral term cannot become negative; thus it will saturate at zero, if the
error and the action try to drive the area to a net negative value.

The transfer function is given by:

$$Kp + (KI/s) \tag{2.9}$$

The integral action adjustment is the integral time T1 (=KI). For a step deviation ‘e’, the integral time or reset time is the time for proportional
action. ‘Reset rate’ is defined as the number of times per minute that the
proportional part of the response is duplicated. Reset Rate is therefore called
‘repeats per minute’, and is the inverse of integral type.

During the design of the PI controller for the buck and boost converter, a closed loop operation is performed. The open loop operation is insensitive to load and line disturbances. So this operation is ineffective.

Therefore, the closed loop operation is selected. The closed loop control uses a feedback signal from the process, a desired value or set point (output voltage) and a control system that compares the two and derives an error signal. The error signal is then processed and used to control the converter to try to reduce the error. The error signal processing can be very complex because of delays in the system. The error signal is usually processed using a Proportional - Integral (PI) controller whose parameters can be adjusted to optimize the performance and stability of the system. Once a system is set up and is stable, very efficient and accurate control can be achieved :

- Input is the voltage error (reference voltage subtracted from the actual voltage)

- Output is the incremental duty ratio.

The controller specifications of a converter are

- Minimum steady state error.
- Less settling time**.**

CHAPTER THREE

MODELING OF PMSM AND DRIVE SYSTEM

3.1 Introduction

This chapter deals with the detailed modeling of a permanent magnet synchronous motor. 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 PI controller in the speed loop. Design of the speed controller is discussed.

3.2 Detailed 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 and angle θr with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor. [8]

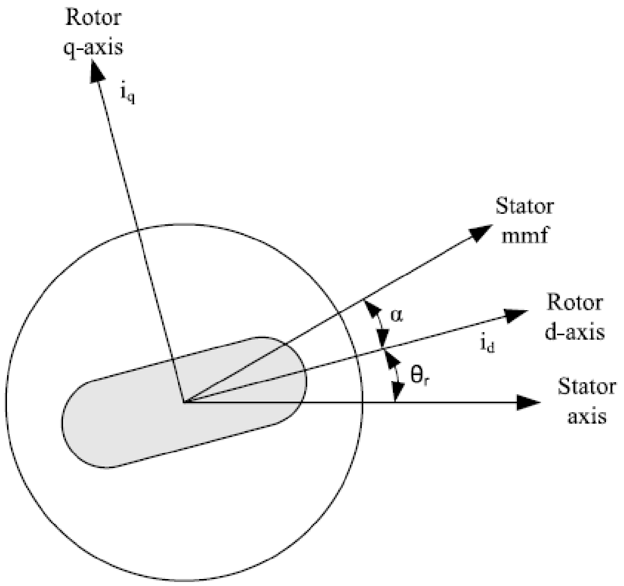


Figure 3.1: Motor axis

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

1) Saturation is neglected.

2) The induced EMF is sinusoidal.

3) Eddy currents and hysteresis losses are negligible.

4) There are no field current dynamics.

Voltage equations are given by:

$$Vq = R_S i_q + \omega_r \lambda_d + \rho \lambda_q \tag{3.1}$$

$$Vd = R_S i_d - \omega_r \lambda_q + \rho \lambda_d \tag{3.2}$$

Flux Linkages are given by:

$$\lambda_q = L_q i_q \tag{3.3}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{3.4}$$

Substituting equations 3.3 and 3.4 into 3.1 and 3.2

$$Vq = R_S i_q + \omega_r (L_d i_d + \lambda_f) + \rho\, L_q i_q \tag{3.5}$$

$$Vd = R_S i_d - \omega_r (L_q i_q) + \rho\, (L_d i_d + \lambda_f) \tag{3.6}$$

Arranging equations 3.5 and 3.6 in matrix form

$$\begin{pmatrix} Vq \\ Vd \end{pmatrix} = \begin{pmatrix} Rs + \rho Lq & \omega_r Ld \\ -\omega_r Lq & Rs + \rho Ld \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \tag{3.7}$$

The developed torque motor is being given by

$$T_e = \frac{3}{2} \left(\frac{p}{2}\right) \left(\lambda_d iq - \lambda_q id\right) \tag{3.8}$$

The mechanical Torque equation is

$$T_e = T_L + B\omega_m + J \frac{d\omega_m}{dt} \tag{3.9}$$

Solving for the rotor mechanical speed form equation 3.9

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

and

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

In the above equations ω_r is the rotor electrical speed where as ω_m is the rotor mechanical speed.

3.2.1 Parks transformation and dynamic dq 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 an currents to dqo variables by using Parks transformation [8]. Converting the phase voltages variables Vabc to Vdqo variables in rotor reference frame the following equations are obtained:

$$\begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_C \end{bmatrix} \tag{3.12}$$

Convert Vdqo to Vabc

$$\begin{bmatrix} V_a \\ V_b \\ V_C \end{bmatrix} = \begin{bmatrix} cos\theta_r & sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} \tag{3.13}$$

3.2.2 Equivalent circuit of permanent magnet synchronous motor

Equivalent circuits of the motors are used for study and simulation of motors. From the d-q modeling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source as described in the following equation $\lambda_f = L_{dm} i_f$ figure 3.2 is obtained.

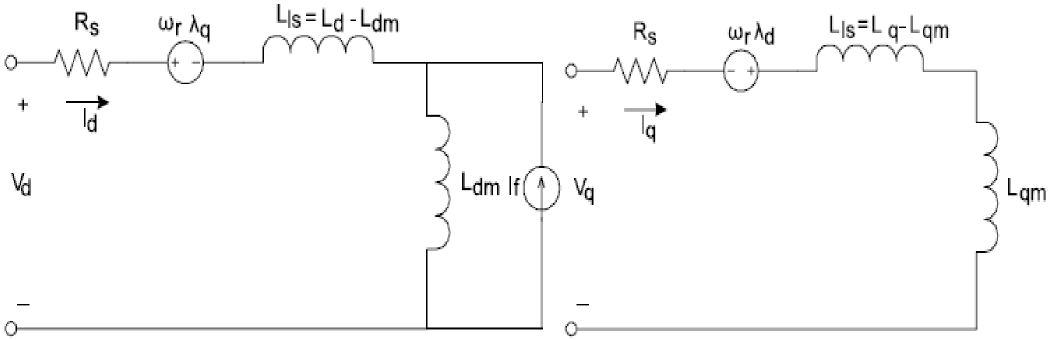


Figure 3.2: Permanent magnet motor electric circuit without damper windings

3.3 SVPWM for three-leg voltage source inverter

The topology of a three-leg voltage source inverter is shown in Figure 3.3. Eight possible switching combinations are generated by the switching network shown in Figure 4.1 Six out of these eight topologies producing a nonzero output voltage are known as the non-zero switching states and the remaining two topologies producing zero output voltage are known as zero switching states.

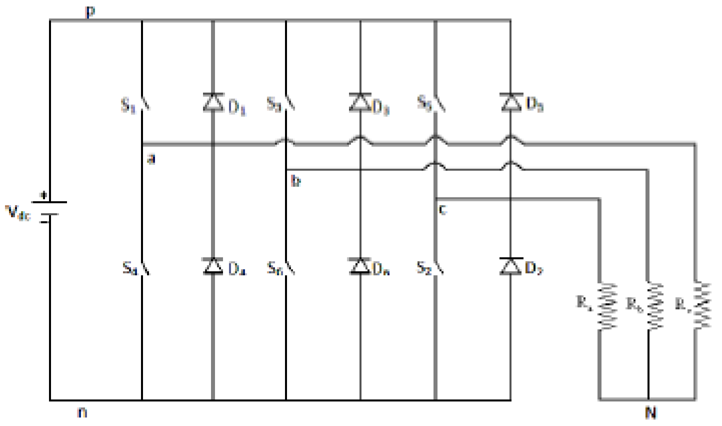


Figure 3.3: Three-phase voltage source inverter

3.4 Voltage space vectors

Space Vector Modulation (SVM) for three-leg VSI is based representation of the three phase quantities as vectors in a two-dimensional (α , β) plane. Considering topology 1 of Figure 3.4, which is repeated in Figure 3.5 a. The line voltages V_{ab} ,V_{bc} and V_{ca} are given by

$$V_{ab} = +V_{dc}$$
$$V_{bc} = 0 \qquad (3.14)$$
$$V_{ca} = -V_{dc}$$

This can be represented in the (α , β) plane as shown in Figure 3.5(b), where voltages Vab ,Vbc and Vca are three line voltage vectors displaced 1200 in space. The effective voltage vector generated by this topology is represented as V1 (pnn) in Figure 3.5.b. The switching network shown in Figure 3.3 has a total of eight possible switching combinations. Each switching combination is shown in Figure 3.4, and is represented according to the phase leg connection, where '*p*' denotes that phase leg is connected to the positive rail of the DC link, and '*n*' denotes that phase leg is connected to the negative rail of the DC link. For example, switching combination '*pnn*' represents the condition where the phase A output terminal Va is connected to the positive DC rail, and phase B and C output terminals Vb and Vc are connected to the negative DC rail.

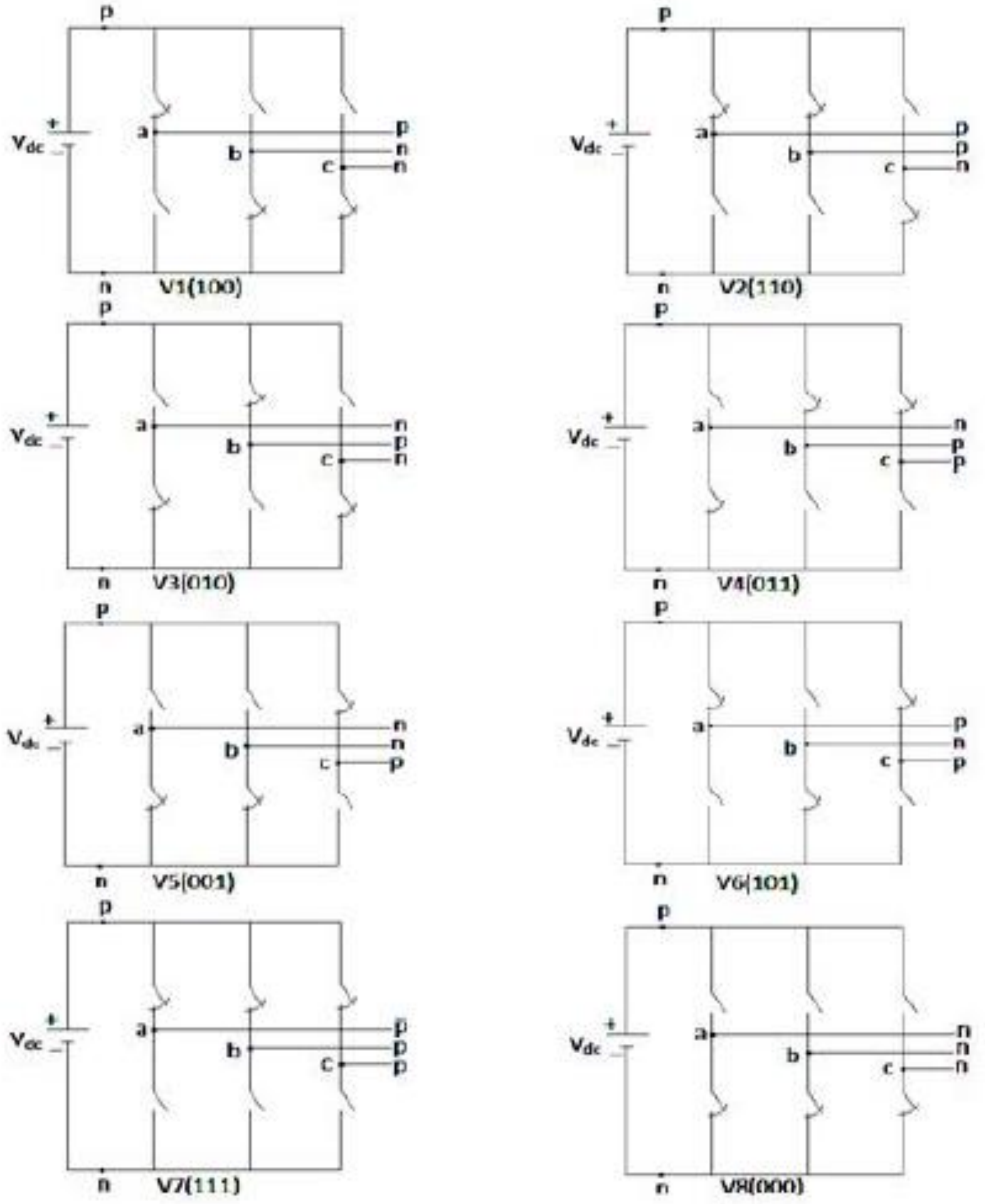


Figure 3.4: Eight Switching state topologies of three-phase inverter

Each switching combination results in a set of three phase voltages at the AC terminal of the switching network. A reference vector $V1$ can be obtained by transforming the reference three-phase voltage into the (α , β) plane, as shown in Figure 3.5.b. A balanced three-phase sinusoidal waveform is obtained when the reference vector is rotating in the (α , β) plane

Proceeding on similar lines the six non-zero voltage vectors (V_1- V_6*) can* be shown to assume the positions shown in Figure 3.6. The tips of these vectors form a regular hexagon (dotted line shown in Figure 3.6). The area enclosed by two adjacent vectors, within the hexagon, is chosen as a sector. Thus there are six sectors numbered 1 to 6 in Figure 3.6.

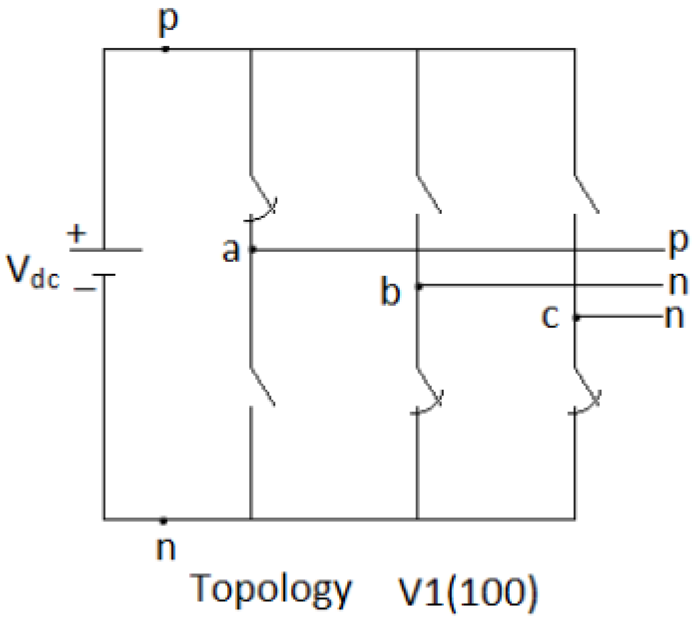


Figure 3.5.a: Topology V1 (100) voltage source inverter

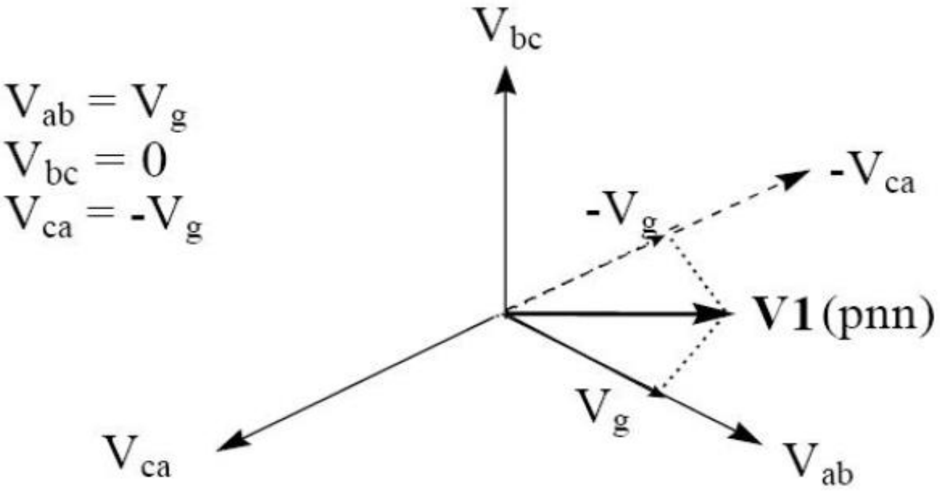


Figure 3.5.b: Topology representation of (α , β) plane

The output line voltages generated by this topology in Figure 3.5.a are given by:

$$V_{ab} = 0$$
$$V_{cb} = 0 \qquad (3.15)$$
$$V_{ca} = 0$$

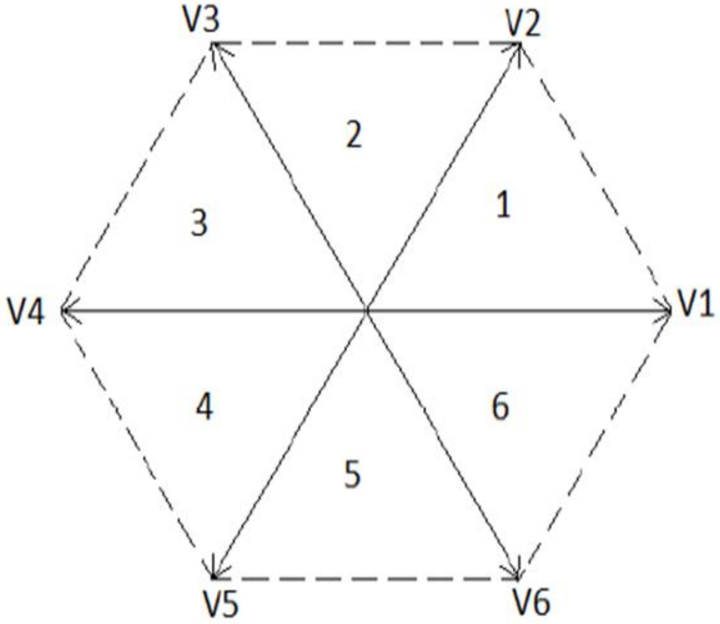


Figure 3.6: Non-zero voltage vectors in the $(\alpha\ ,\ \beta)$ plane

The output voltages are represented as vectors which have zero magnitude and hence are referred to as zero-switching state vectors or zero voltage vectors. The position at origin in the $(\alpha\ ,\ \beta)$ plane is as shown in Figure 3.5.b. A total of eight vectors are obtained by transforming the three-phase voltages into the a - b coordinate and the same are called switching state vectors.

3.5 Space vector modulation

The desired three phase voltages at the output of the inverter could be represented by an equivalent vector V rotating in the counter clock wise direction as shown in Figure 3.8.a. The magnitude of this vector is related to the magnitude of the output voltage as shown in Figure 3.8.b and the time this vector takes to complete one revolution is the same as the fundamental time period of the output voltage. [8]

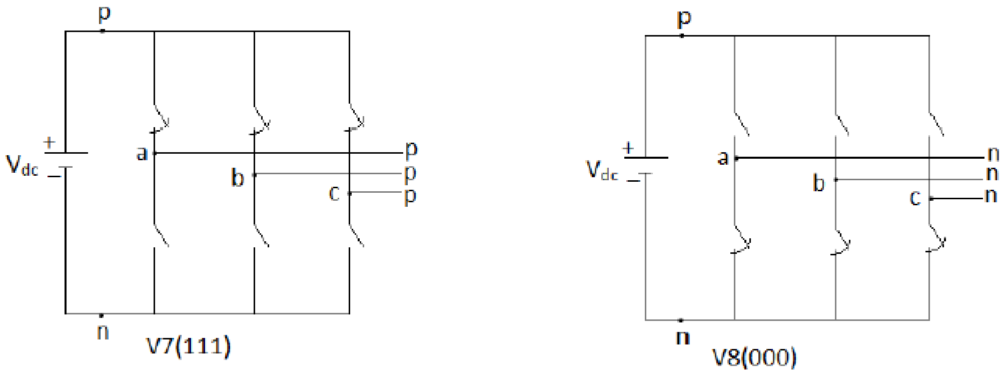


Figure 3.7.a: Zero output voltage topologies

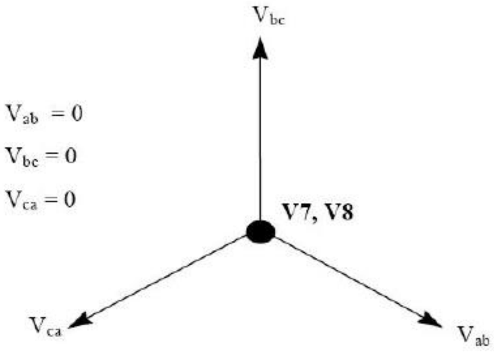


Figure 3.7.b: Representation of the zero voltage vectors in the (α , β)

When the desired line-to-line output voltage vector V is in sector 1, vector V could be synthesized by the pulse-width modulation (PWM) of the two adjacent switching state vectors V1 (pnn) and V2 (ppn), the duty cycle of each being d1 and d2, respectively, and the zero vector (V7 (nnn) / V8 (ppp)) of duty cycle d0

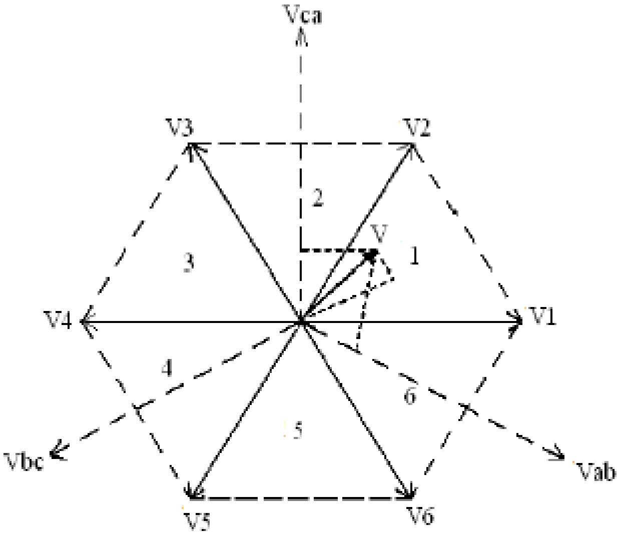


Figure 3.8.a: Output voltage vector in the (α , β) plane

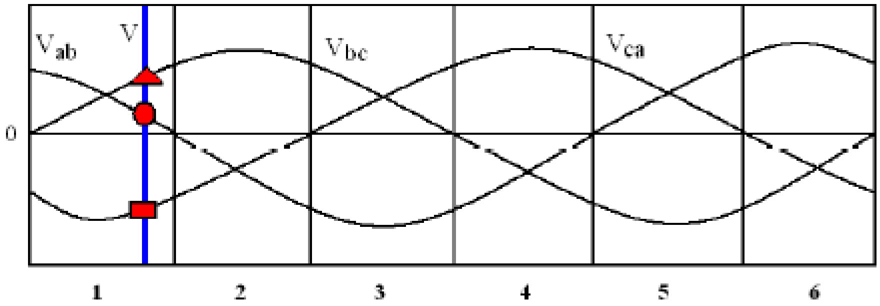


Figure 3.8.b: Output line voltage

3.6 Two-Dimensional space vector

For any balanced three-phase variable V_a V_b V_c where *V* be the voltage vector, there is a relationship

$$V_a + V_b + V_c = 0 \tag{3.16}$$

The above equation suggests that the three variables could be mapped into a vector $\vec{v}$ on the orthogonal(α , β) plane where

$$\vec{V} = \vec{V}\alpha + j\vec{V}\beta \tag{3.17}$$

The transformation for this orthogonal co-ordinate mapping, sometime called 3/2 transformation, is expressed asbv

$$[V_\alpha \quad V_\beta]^T = T_2[V_a \quad V_b \quad V_c]^T \tag{3.18}$$

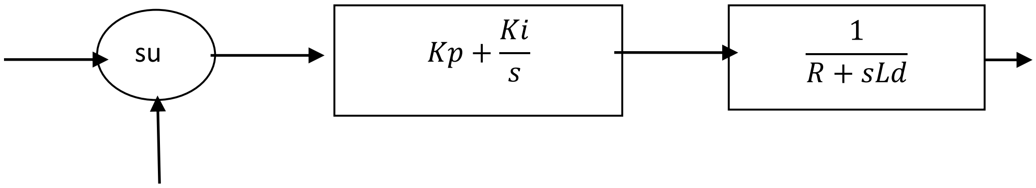
where T is the transformation matrix and is expressed as

$$T = \frac{2}{3}\begin{bmatrix} 1 & -{}^{1}\!/_{2} & -{}^{1}\!/_{2} \\ 0 & {}^{\sqrt{3}}\!/_{2} & -{}^{\sqrt{3}}\!/_{2} \end{bmatrix} \tag{3.19}$$

3.7 Calculation of PI constants Kp and Ki

PI controller to regulate the d component of the stator current. The reference value, I_{dref}, is zero in this thesis since there is no flux weakening operation. The d component error of the current, *Id*, is used as an input for the PI regulator. Moreover, there is another PI controller to regulate the q component of the current.[9]

Drive PI constant Kp and Ki for current



$$\frac{Kp + {}^{Ki}\!/_{s}}{Ra + sLd} \tag{3.20}$$

multiply by (s)

$$\frac{(sKp+Ki)}{s(sLd+Ra)} \tag{3.21}$$

$$\frac{Kp(s+{}^{Ki}/_{Kp})}{sLd(s+{}^{Ra}/_{Ld})} \tag{3.22}$$

$$\frac{Ki}{Kp} = \frac{Ra}{Ld} \tag{3.23}$$

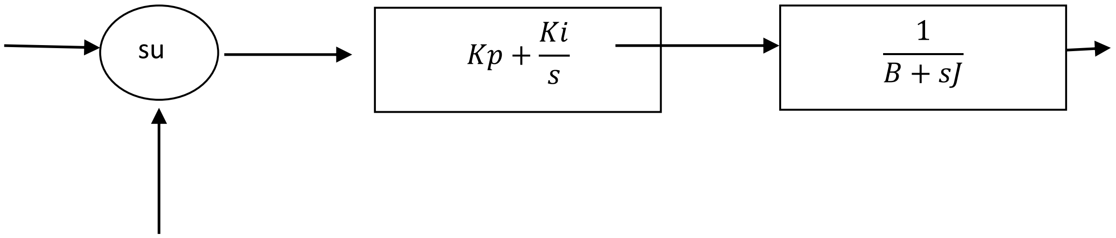
$$\frac{Kp}{Ld} = \omega_c \tag{3.24}$$

$$\omega_c = 2\pi f_c \tag{3.25}$$

$$Kp = 2\pi f_c L_d \tag{3.26}$$

$$Ki = \frac{Ra}{Ld} * Kp \tag{3.27}$$

Drive PI constant Kp and Ki for speed:



$$\frac{Kp+{}^{Ki}/_{s}}{Js+B} \tag{3.28}$$

$$\frac{(sKp+Ki)}{s(Js+B)} \tag{3.29}$$

$$\frac{kp}{Js}\left[\frac{s+{}^{Ki}/_{Kp}}{s+{}^{J}/_{B}}\right] \tag{3.30}$$

$$\frac{Ki}{Kp} = \frac{J}{B} \tag{3.31}$$

$$\frac{Kp}{J} = \omega_c \tag{3.32}$$

$$\omega_c = 2\pi f_c \tag{3.33}$$

$$Kp = 2\pi f_{\text{c}} J \tag{3.34}$$

$$Ki = \frac{J}{B} Kp \tag{3.35}$$

CHAPTER FOUR

SIMULATION AND ANYLYISIS RESULTS

4.1 Simulink simulation of PMSM drive

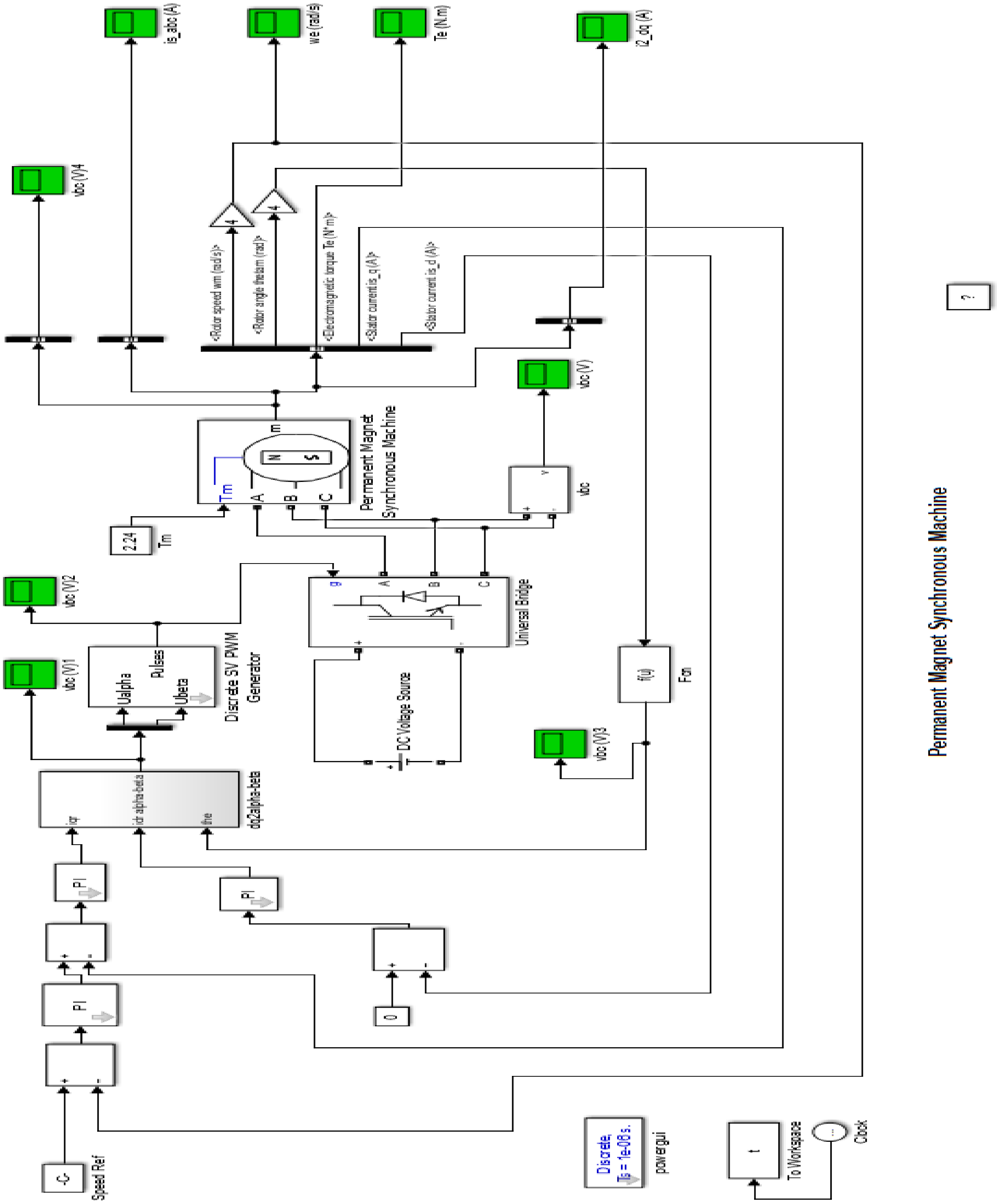


Figure 4.1: Derivation of permanent magnet synchronous machine

The PM motor drive simulation was built in several steps like dq0 phase transformation to alpha-beta variables, calculation torque and speed, and control circuit.

The dq0 phase transformation to alpha-beta variables is built using Parks transformation and for the dqo to alpha-beta the reverse transformation is used.

Parks transformation used for converting Idqo to alpha-beta is shown in Figure 4.2

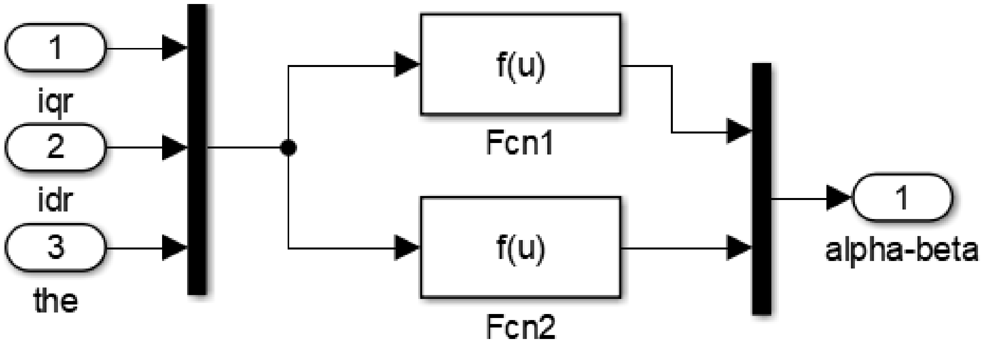


figure 4.2: Parks transformation

The inverter is implemented in Simulink as shown in Figure 4.3 The inverter consists of the "universal bridge" block from the power systems tool box with the parameters of the IGBT that was presented in chapter 2. The voltages and currents in the motor and in all the devices of the inverter can be obtained

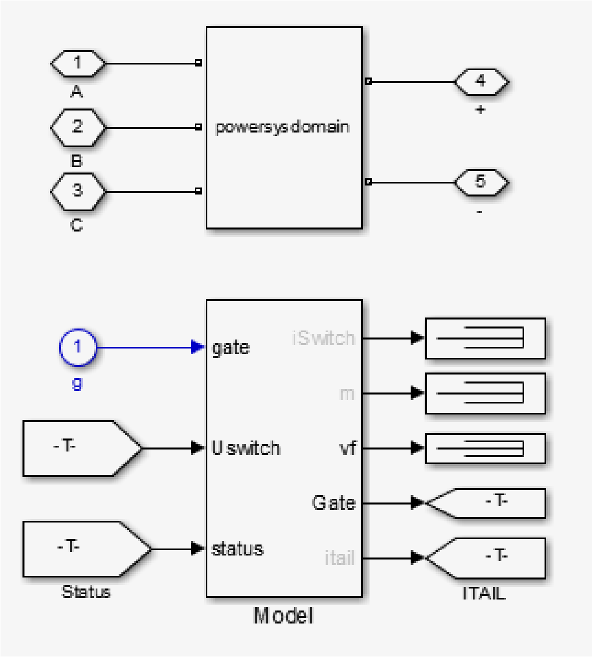


Figure 4.3: Voltage source inverter

The SVPWM is considered as a better technique of PWM implementation as it has advantages over SPWM in terms of good utilization of dc bus voltage, reduced switching frequency and low current ripple by using switching pattern#1 as shown in Figure 4.4

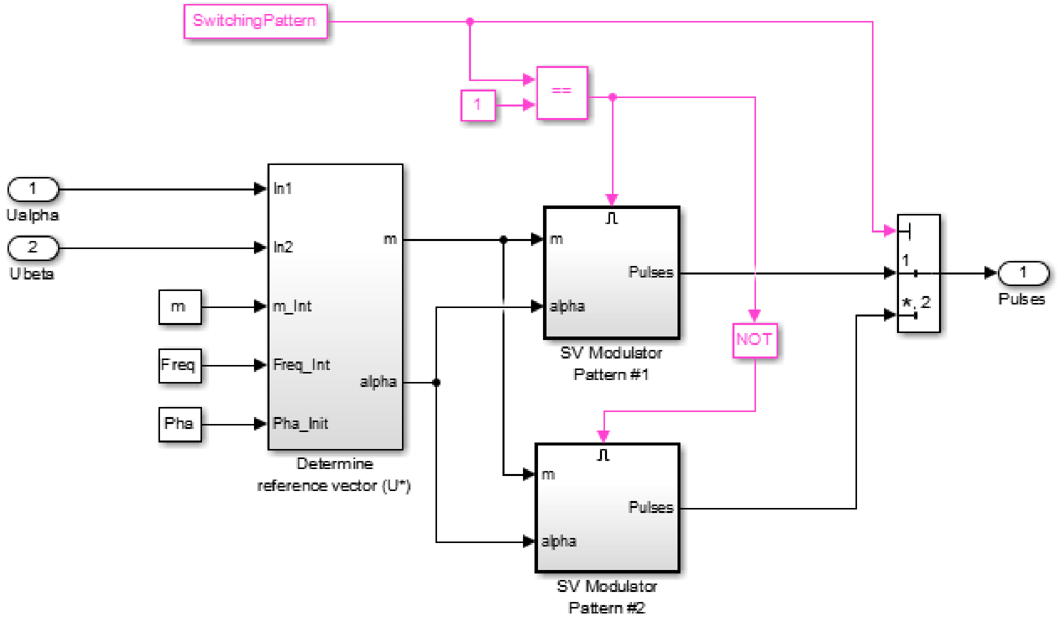


Figure 4.4: Block diagram of SVPWM

The whole drive system is simulated in MATLAB/Simulink. Simulation results are given at electrical speeds of 418.67 radians per second and 266.67 (HZ).

4.2 Case study

we attempt to control the speed and torque of PMSM using PI controller and discrete SV PWM by comparing it with reference speed (418.67 radian per second).

Table 4.1: Simulation system equipment

NO	DEVICE	UNIT
1	Sum	4
2	Function	1
3	PI	3
4	Discrete SV PWM	1
5	Dq2alpha-beta	1
6	Scope	7
7	PMSM	1
8	Universal bridge	1
9	Clock	1
10	Power gui	1
11	Work space	1
12	Gain	2
13	Speed ref	1
14	Tm	1
15	Dc voltage source	1
16	Demux	1
17	Bus selector	2

Table 4.2: Result of K_i and K_p Constant

	current	speed
Ki	16246.15	5.31
Kp	19.2	2.32

4.3 Simulation Results

Simulation for operation at 418.68 rad/sec:

SVPWM current control

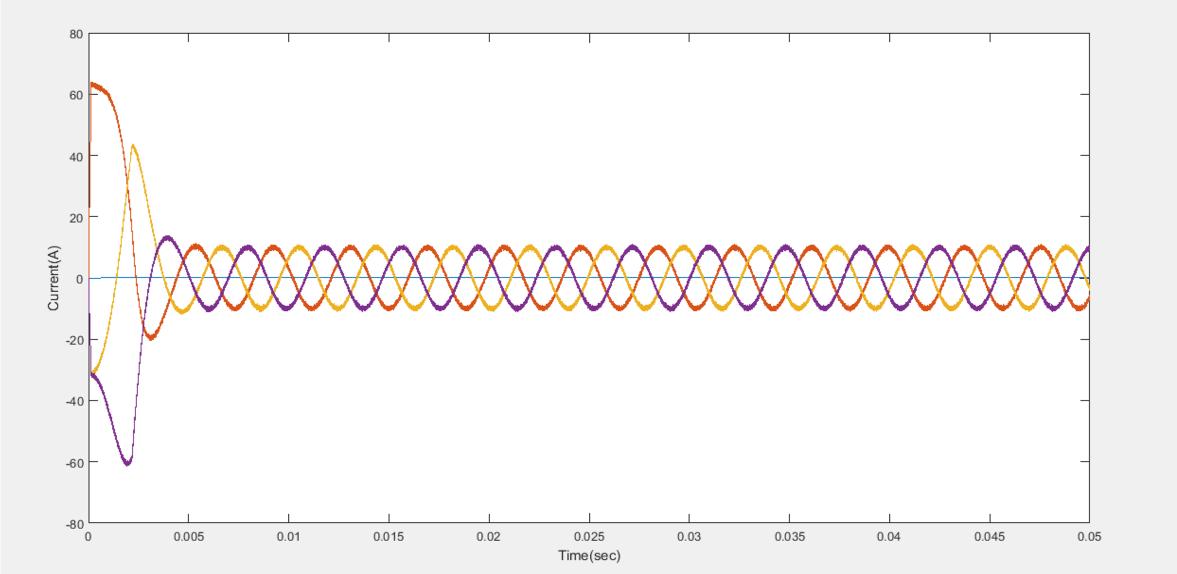


Figure 4.5: Iabc currents with SVPWM control at 418.67 rad/s

Figure 4.5 shows the three phase currents as a result of the PWM current control obtained from Park's reverse transformation. It is clear that the current is non sinusoidal at the starting and becomes sinusoidal when the motor reaches the controller command speed at steady state.

Table 4.3: Current characteristics

Symbol	Name	Value
I_{max}	Maximum current	10.04 A
I_{rms}	Rms current	7.097 A
T_d	Delay time	0.004 msec
Tr	Rise time	0.005 msec
M_p	Maximum overshoot	11.7%

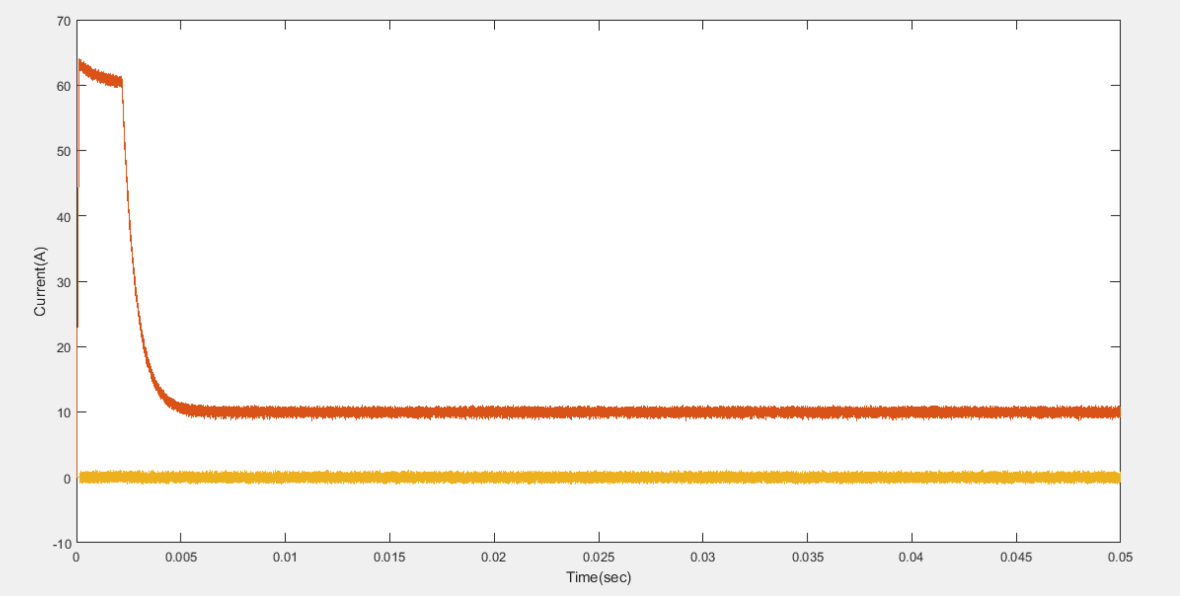


Figure 4.6: Idqo Currents with SVPWM control at 418.67 rad/s

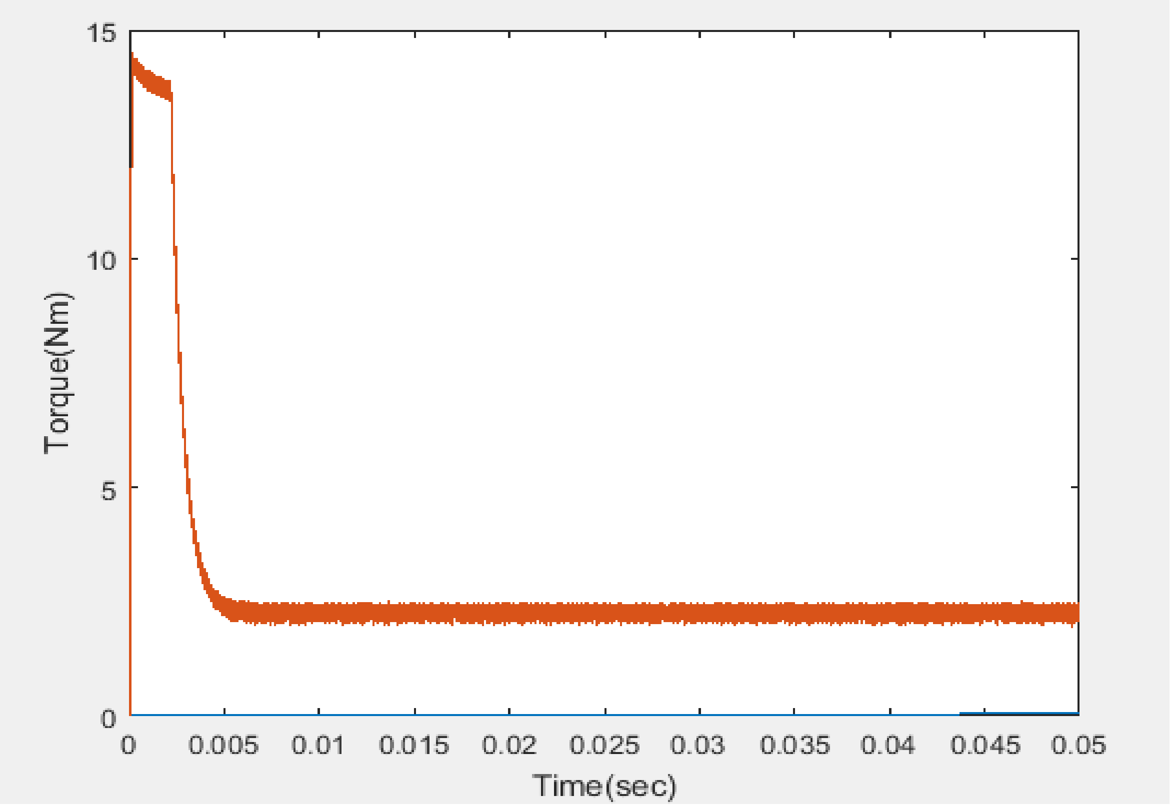


Figure 4.7: Developed torque with SVPWM control at 418.67 rad/sec

Figure 4.7 shows the developed torque of the motor. The starting torque is twice the steady state value. The developed torque is the same as the load torque (2.24Nm) under steady state condition.

Table 4.4: Torque characteristics

Symbol	Name	Value
T_m	Motor torque	2.24 Nm
T	Output torque	2.26 Nm
M_p	Maximum overshoot	11.7%
T_p	Peak time	0.005 msec

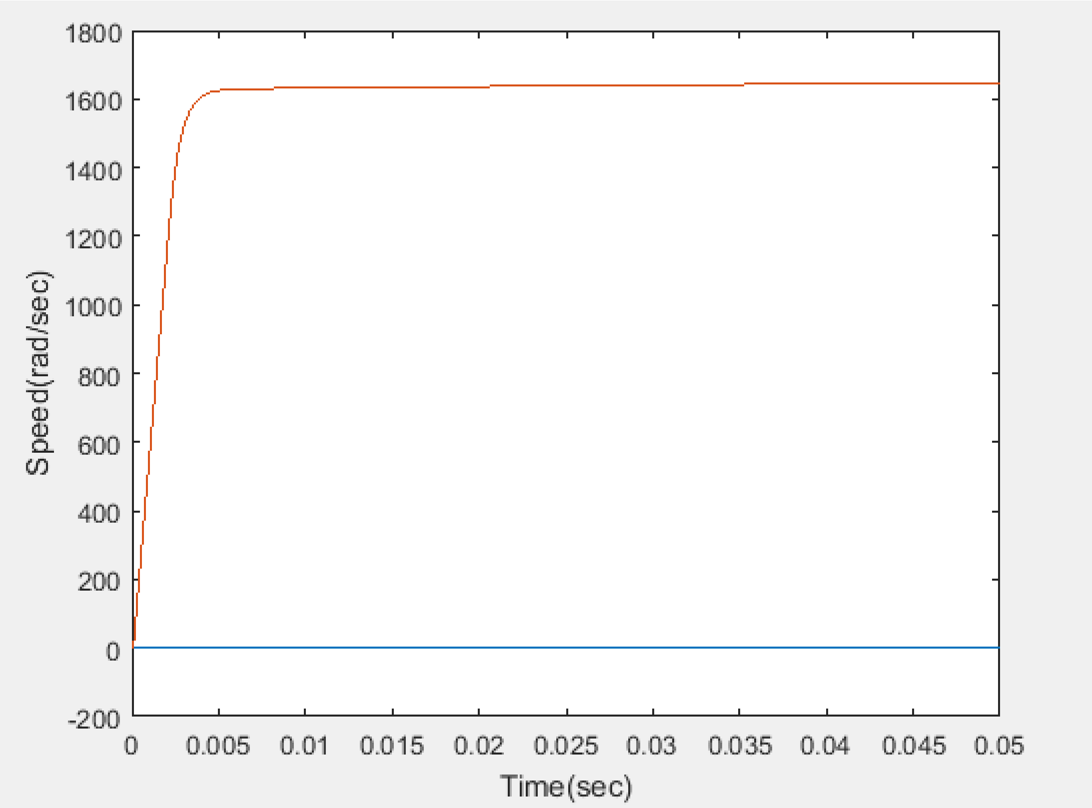


Figure 4.8 Motor Electrical Speed with SVPWM Controller at 418.67 rad/s

Figure 4.8 shows a variation of the speed with time. The steady state speed is the same as that of the commanded reference speed.

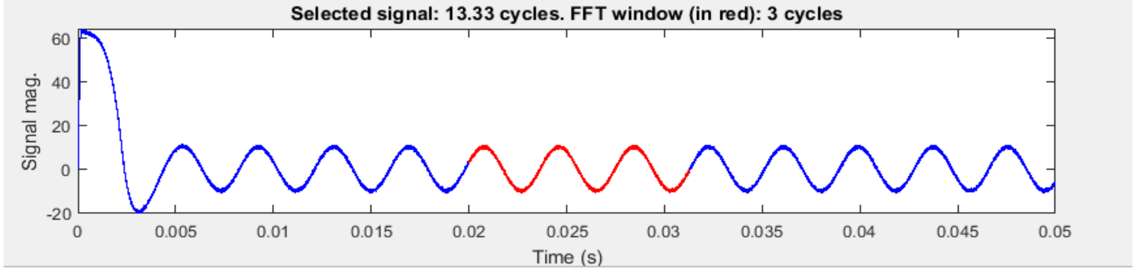
Table: 4.5 Speed characteristics

Symbol	Name	Value
ω_{ref}	Reference speed	1676.67 rad/sec
ω_r	Running speed	1639 rad/sec
M_p	Maximum overshoot	11.5%
T_p	Peak time	.005 msec

4.4 Harmonic spectrum and total harmonic distortion

Harmonic content in a voltage or current wave form determines the quality of power. The power quality is judged by a factor called Total Harmonic Distortion (THD). The higher the THD the lower is the power quality.

Harmonic contents in phase voltages and currents are determined using Fast Fourier Transform (FFT). The results are given below for SVPWM modes of current control. These results are obtained using Simulink FFT tool of Powergui to display the frequency spectrum of voltage and current waveforms and THD content. These signals are stored in the workspace in the ASM structure with time variable generated by the Scope block. Because the model is discretized, the signal saved in this structure is sampled at a fixed step and consequently satisfies the FFT tool requirements.



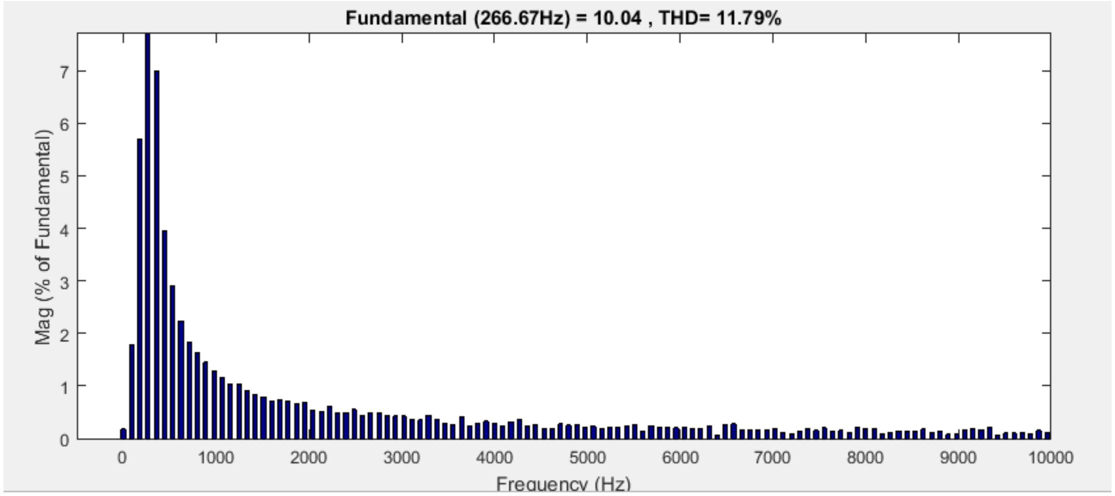


Figure 4.9: Phase current FFT with SVPWM control at 418.67 rad/s

Figure 4.9 shows the phase current waveform with PWM control and the corresponding harmonic spectrum. The value of THD is 11.79%. Since the motor offers a large impedance to higher harmonic voltages, the current drawn by the motor is sinusoidal.

The voltage THD% is higher than current THD% which demonstrates that the motor acts like a filter for the high order harmonics (low pass filter) that were attenuated by the motor inductances. The voltage and currents THD% for both methods where within IEEE 519 recommended limits.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A detailed Simulink model for a PMSM drive system with field-oriented control has being developed and operation below and above rated speed has been studied using current control schemes.

Simulink has been chosen from several simulation tools because its flexibility in working with analog and digital devices. Mathematical models can be easily incorporated in the simulation and the presence of numerous tool boxes and support guides simplifies the simulation of large system compared to Spice.

Simulink is capable of showing real time results with reduced simulation time and debugging.

In the present simulation measurement of currents, voltages, torque and speed in each part of the system is possible, thus permitting the calculation of instantaneous or average losses, efficiency of the drive system and total harmonic distortion.

Usually in such a drive system the inverter is driven by SV PWM
current controllers. A comparative study has been made of the current control schemes in terms of switching frequency, device losses, power quality, speed error and current control ability.

This study proves that PWM current controllers have constant switching frequency and lower THD of the input voltage waveforms. The error between the speed command and the actual speed is small.

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. The simulated system has a fast response with practically zero steady state error thus validating the design method of the speed controller.

5.2 Recommendations

The implementation of additional control techniques like unity power factor control, constant mutual air gap flux linkages control, optimum torque per ampere control and sensor less control can be taken up for detail simulation and performance calculation of PMSM drive systems. Detailed modeling and simulation of other types of synchronous motor drives can also be taken up for transient and steady state analysis.

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APPENDIX

System data

Symbol	Name	Value
P_{out}	Output power	843W
I_m	Maximum line current	10.5A
N	Speed	4000 r.p.m.
V_{dc}	Source voltage	340V
R_a	Armature resistance	0.55 Ω
L_d	d-axis inductance	0.65mH
L_q	q-axis inductance	0.65mH
J	Motor inertia	$7.58*10^{-5}$kg.m^2
B	Viscous damping coefficient	3.47*10Nm/s
λ	PM flux	$37.7*10^{-3}$mwb
P	Number of poles	8
R_c	Stator resistance	300 Ω