PERFORMANCE INVESTIGATION OF INTELLIGENT POWER MODULE BASED PMSM DRIVE

बुद्धिमान शक्ति मॉड्यूल आधारित स्थायी चुंबक तुल्यकालिक मोटर ड्राइव की निष्पादन जांच

Thesis
Submitted to the
MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY, UDAIPUR

In the partial Fulfillment of the Requirement for the Degree

of
Master of Technology
IN
ELECTRICAL ENGINEERING
(POWER ELECTRONICS)
BY
KUSHAGRA KHAMESRA
(2013)

COLLEGE OF TECHNOLOGY AND ENGINEERING
MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
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(With specialization in Power Electronics)

By

Mr. Kushagra Khamesra

2013

COLLEGE OF TECHNOLOGY AND ENGINEERING
MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
UDAIPUR

Dated: …………….

CERTIFICATE－I

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CERTIFICATE – II

This to certify that this entitled "**PERFORMANCE INVESTIGATION OF INTELLIGENT POWER MODULE BASED PMSM DRIVE.**" submitted for the degree of **Master of Technology** in the subject of **Power Electronics** embodies bonafide research work carried out by **Mr. Kushagra Khamesra** under my guidance and supervision and that no part of this thesis has been submitted for any other degree. The assistance and help received during the course of investigation has been fully acknowledged. The draft of the thesis was also approved by the advisory committee on…………

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CERTIFICATE – III

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ABSTRACT

Permanent magnet synchronous motor (PMSM) has been widely used in high performance drive applications for its advantages such as compactness, high efficiency, reliability and suitability to environment. Due to its high power density and smaller size, PMSM has evolved as the preferred solution for speed and position control drives on machine tools and robots. 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. Permanent magnet synchronous motors are widely used in low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles.

In order to overcome the inherent coupling effect and the sluggish response of scalar control the vector control is employed. By using the vector control, the performance of the AC machine can be made similar to that of a DC machine. In this work to achieve high performance the vector control of the Permanent magnet synchronous motors drive is employed. The simulation of PMSM is developed using SIMULINK. The effectiveness of the proposed control method is verified by simulation based on MATLAB. The simulation results along with the case study is presented and explained in detail.

सारांश

स्थायी चुंबक तुल्यकालिक मोटर (PMSM) व्यापक रूप से इस तरह की सघनता, उच्च क्षमता, विश्वसनीयता और पर्यावरण के लिए उपयुक्तता के रूप में अपने फायदे के लिए उच्च प्रदर्शन ड्राइव अनुप्रयोगों में इस्तेमाल किया गया है. इसकी उच्च ऊर्जा घनत्व और छोटे आकार के कारण, PMSM मशीन टूल्स और रोबोट पर गति और स्थिति को नियंत्रण ड्राइव के लिए पसंदीदा समाधान के रूप में विकसित किया गया है. एक स्थायी चुंबक तुल्यकालिक मोटर (PMSM) बल्कि विद्युत का उपयोग कर से हवा खाई चुंबकीय क्षेत्र का उत्पादन करने के लिए स्थायी चुंबक का उपयोग करता है कि एक मोटर है. इन मोटरों कई अनुप्रयोगों में प्रयोग के लिए शोधकर्ताओं और उद्योग के हित को आकर्षित करने, महत्वपूर्ण लाभ है. स्थायी चुंबक तुल्यकालिक मोटर्स व्यापक रूप से कंप्यूटर परिधीय उपकरण, रोबोटिक्स, समायोज्य गति ड्राइव और बिजली के वाहनों के रूप में कम और मध्यम शक्ति अनुप्रयोगों में उपयोग किया जाता है.

निहित युग्मन के प्रभाव से उबरने के लिए और अदिश नियंत्रण वेक्टर नियंत्रण की सुस्त प्रतिक्रिया कार्यरत है आदेश में. वेक्टर नियंत्रण का उपयोग करके, एसी मशीन का प्रदर्शन एक डीसी मशीन के समान बनाया जा सकता है. उच्च प्रदर्शन को प्राप्त करने के लिए इस काम में स्थायी चुंबक तुल्यकालिक मोटर्स ड्राइव के वेक्टर नियंत्रण के लिए कार्यरत है. PMSM का अनुकरण SIMULINK उपयोग कर विकसित किया है. प्रस्तावित नियंत्रण विधि का प्रभाव MATLAB के आधार पर अनुकरण द्वारा सत्यापित है. मामले के अध्ययन के साथ साथ सिमुलेशन परिणाम प्रस्तुत किया और विस्तार से समझाया गया है.

CONTENTS

4. DESCRIPTION OF THE DRIVE SYSTEM

6. VECTOR CONTROLLED PMSM DRIVE IN MATLAB/SIMULINK

7. SIMULATION RESULTS

8. PRACTICAL IMPLEMENTATION OF PMSM DRIVE SYSTEM

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CHAPTER 1

INTRODUCTION

This chapter covers general introduction about permanent magnet synchronous motor, its types and control fundamentals. Main benefits and drawbacks of the various motor types. Comparison between permanent magnet synchronous motor and induction motor is also discussed. It also includes objectives of the dissertation.

1.1 GENERAL OVERVIEW

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

Many types of electric motors have been used in the industry for different purposes: cranes, spinning machines, public transportation and so on (Stefanovic). AC motors are widely used and ac drives are subject of study for many researchers (Kerkman, Pillay). Recently, ac drives in vehicle applications are gaining attention due to pollution and fuel price problems.

Permanent Magnet Synchronous Motor has gained popularity especially in the automation sector due to its compact size, high efficiency, and faster response. As reliability and cost of modern PMSM drives are of importance, advanced control techniques have been developed. The PMSM is very similar to the standard wound rotor synchronous machine except that the PMSM has no damper windings and excitation is provided by a permanent magnet instead of a field winding. The elimination of field coil, dc supply and slip rings reduce the motor loss and complexity.

Several failures afflict electrical motor drives, and so far, redundant or conservative design has been used in every application where continuity of operations is a key feature. This is the case of home and civil appliances, such as air conditioning/heat pumps, engine cooling fans, and electric vehicles (EVs), where reliability is a key issue. Fault tolerance has become an increasingly interesting topic in the last decade where the automation has become more complex. The objective is to give solutions that provide fault accommodation to the most frequent faults and thereby reduce the costs of handling the faults. In submerged pumps or hostile environments where accessibility to the drive and to the sensors is tedious and, nevertheless, continuity of operation is mandatory even in case of fault occurrence, a sensor less algorithm is indispensable to maintain the availability and therefore increase the reliability. Due to its capability of field-weakening control, high efficiency, and high power density, permanent-magnet synchronous motors (PMSMs) are becoming competitive in many applications such as railway electric propulsion power trains, EVs, or hybrid EVs.

The induction motor has in the past been the most deployed motor type on the industrial market but has in recent years been or will be penetrated by PM motors. The reason for this has to be found in the increasing demand for operating systems as energy efficient as possible and the fact that PM motors have higher power density implying less material to transport.

However, PM motors needs a measurement of the rotor position in order to control the motor in a robust way. PM motors cannot be operated in open loop due to the highly unstable behavior of the motor dynamics. In more than ten years there have been extensive researches in finding reliable position sensor less methods to estimate the rotor position from the applied voltages and the consumed currents.

1.2 Classification of PM electric machines

In general, PM electric machines can be classified as shown in figure 1.1.

Depending on the design of the machine whether it for DC or AC excitation, PM electric machines can be first classified into two groups, namely, PMDC and PMAC type. The structure of PMDC machines is very similar to the conventional DC commutator machines. The only difference is the use of permanent-magnets in the place of field windings. The commutator and the brushes still exist in these machines and they still suffer the problems associated with conventional DC commutator machines.

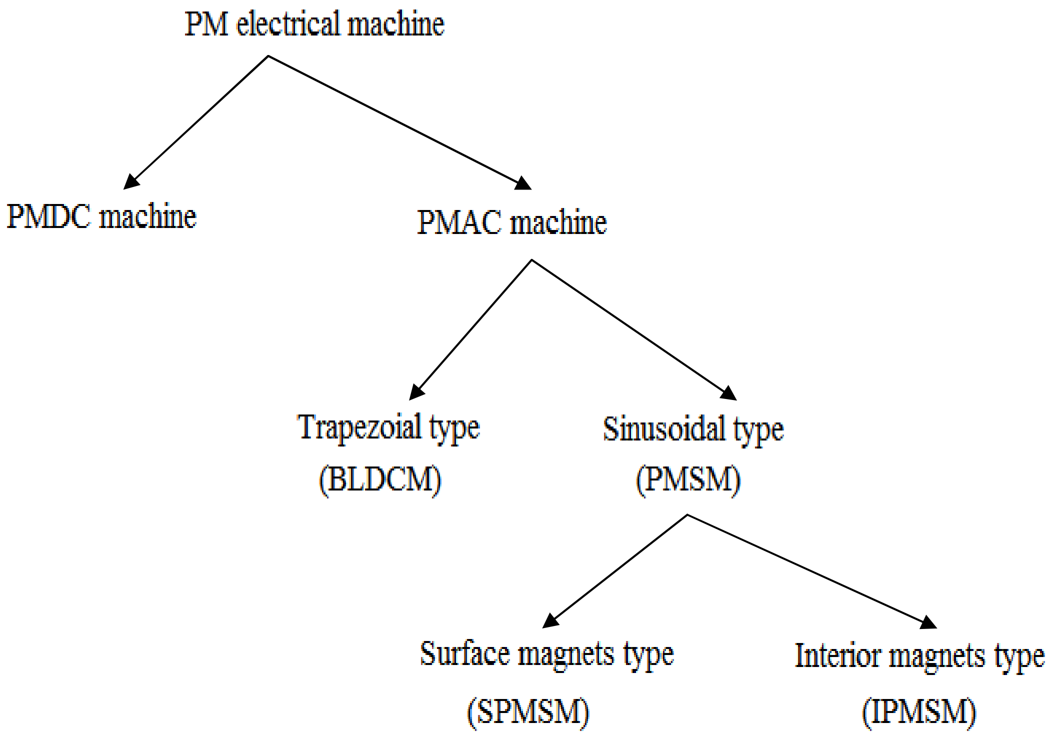
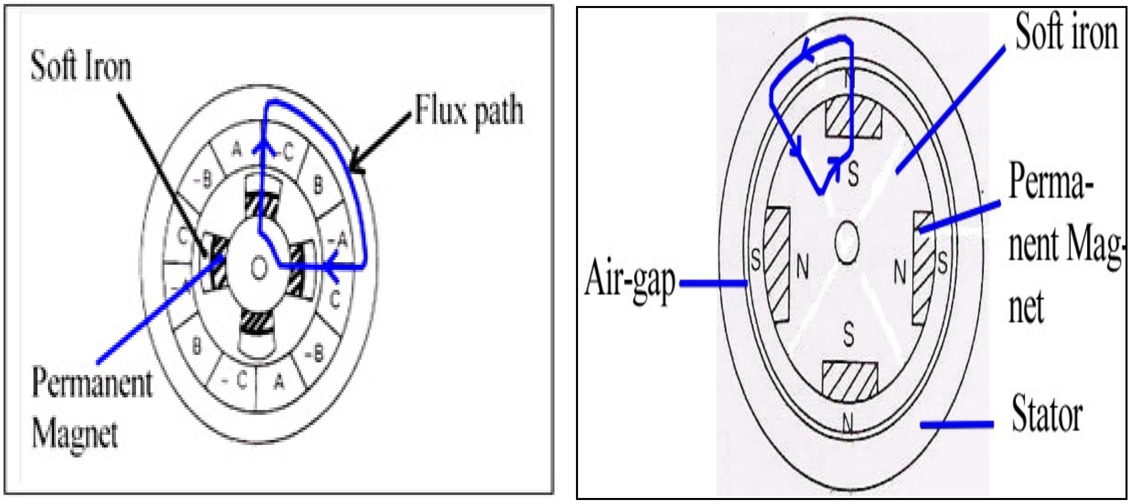


Figure 1.1: Classification of PM electric machines.

The PMAC machines are synchronous machines, which the field is generated by permanent magnets located in the rotor. In these machines, the commutator and the brushes do not exist making the machine structure very simple and eliminating the problems, such as brush wear, high rotor inertia, which associate with PMDC machines. This makes the PMAC machines the most attractive machine type among the PM electric machines. The PMAC machines can be further classified into trapezoidal and sinusoidal types as shown in figure 1.1. The trapezoidal PMAC machines induce a trapezoidal back-EMF voltage waveform in each stator phase winding during rotation, whereas sinusoidal PMAC machines induce a sinusoidal back-EMF voltage waveform.

For torque production, the trapezoidal PMAC machines are excited from rectangular current waveforms, whereas sinusoidal PMAC machines require sinusoidal current excitation of the stator. The trapezoidal PMAC machines, which are also called “brushless DC motors” (BLDCM), were developed first because of the simple control of those machines. However, the presence of torque ripples in those drives rejects their usage in high performance motion control applications. The development of sinusoidal PMAC machines came next in late 1970s and 1980s due to the possibility of high performance control of those machines using vector control principles first used for induction machines (Jahns). The sinusoidal PMAC machines are the most suitable PMAC machine type to compete with the induction machines in the most of the induction machine drive applications. Therefore, they are getting a growing attention in recent years. Since these machines are closely related to the conventional synchronous machines, they are also called PM synchronous machines (PMSMs). It should be mentioned that except for special applications, in general, the PMSMs are not built with damper windings in the rotor, mainly due to the high manufacturing cost. Hereinafter the PMSMs referred to PM synchronous machines without having damper windings in the rotor.

Different rotor configurations exist for PMSMs depending on how the magnets are placed in the rotor (Jahns, Slemon). The two common types, namely, surface magnets type and interior magnets type are shown in figure 1.2. In surface magnets type the magnets are mounted on the surface of the rotor core, whereas in interior magnets type the magnets are placed inside the rotor core. Here in after the PMSMs with surface magnets rotor configurations are referred to as SPMSMs and PMSM with interior magnets rotor configurations are referred to as IPMSMs.



(a) **(b)**

Figure 1.2: Motor cross sections showing different rotor configurations for PMSMs: (a) Surface magnets type (b) Interior magnets type.

Main benefits and drawbacks of the motor types.

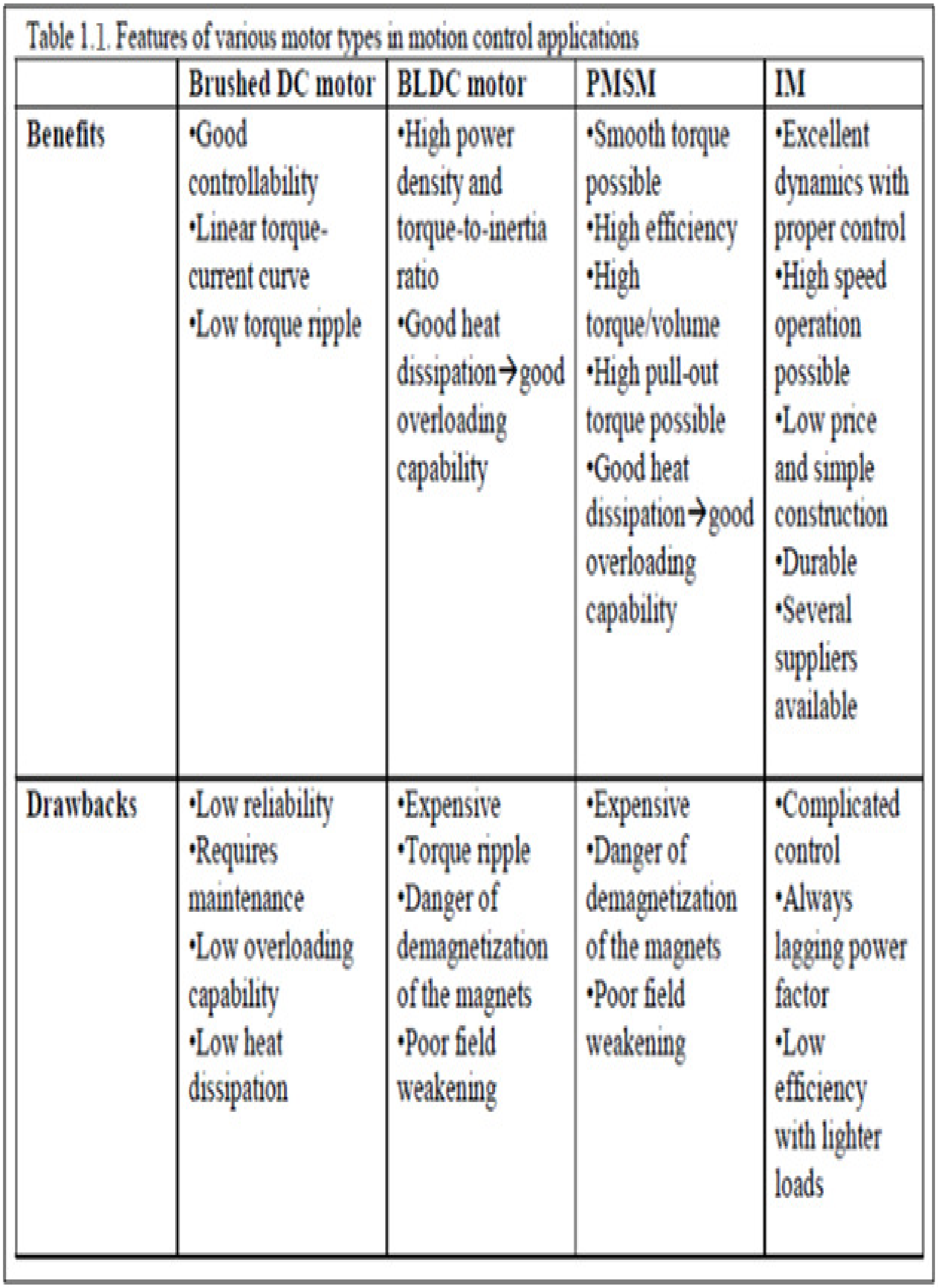


Table 1.1. Features of various motor types in motion control applications

	Brushed DC motor	BLDC motor	PMSM	IM
Benefits	•Good controllability •Linear torque-current curve •Low torque ripple	•High power density and torque-to-inertia ratio •Good heat dissipation→good overloading capability	•Smooth torque possible •High efficiency •High torque/volume •High pull-out torque possible •Good heat dissipation→good overloading capability	•Excellent dynamics with proper control •High speed operation possible •Low price and simple construction •Durable •Several suppliers available
Drawbacks	•Low reliability •Requires maintenance •Low overloading capability •Low heat dissipation	•Expensive •Torque ripple •Danger of demagnetization of the magnets •Poor field weakening	•Expensive •Danger of demagnetization of the magnets •Poor field weakening	•Complicated control •Always lagging power factor •Low efficiency with lighter loads

Table 1.1: Features of various motor types

1.3 Control fundamentals for PMSMs

Since PMSMs are synchronous machines, the accurate torque can be produced in these machines only when the AC excitation frequency is precisely synchronized with the rotor frequency. Therefore, the fundamental requirement in control design of PMSMs is the assurance of precise synchronization of machine's excitation with the rotor frequency. The direct approach to achieve this requirement is the continuous measurement of the absolute rotor angular position and, the excitation of the machine accordingly as shown in figure 1.3. This concept is also known as self synchronization (Jahns) and it assures that the PMSM does not go out of synchronization during operation.

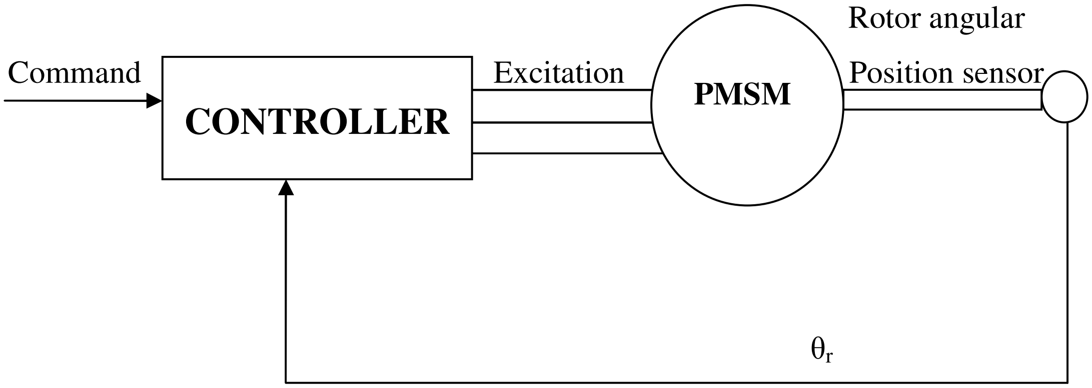


Figure 1.3: The self synchronization concept for PMSMs, which uses rotor angular position feedback to synchronize the AC excitation and the rotor frequency.

1.3.1 Scalar control

The principle of the scalar control is to maintain a constant V/Hz ratio almost through the whole speed range operation since only the magnitude and frequency of the supply voltages is controlled. The V/Hz ratio is calculated from the nominal values (voltage and frequency) of the PMSM. By maintaining a constant V/Hz ratio the stator flux of the PMSM can be maintained relatively constant in steady state. If the V/Hz ratio increases then the PMSM becomes overexcited and if it decreases then it becomes under excited (Stulrajter). At very low speeds it is necessary to compensate for the stator resistance voltage drop so a V/Hz ratio higher than the nominal one is needed. The scalar control is the most common control strategy used for IM drives.

The PMSM scalar control is a good alternative in applications where good dynamic performance is not required (fans, pumps, blowers). Scalar control is performed without the need of a position encoder and the speed of the rotor can be estimated by looking at the frequency of the supply voltage (Stulrajter). When using scalar control there is no need for high capability DSP as in the case of vector control.

Some PMSMs have so called build in damper windings which help to stabilize the PMSM especially when scalar controlled. The damper windings basically are similar to the squirrel cage rotor of an IM. In a PMSM the damper windings produce some amount of asynchronous torque similarly as in an IM when needed thus helping the PMSM to synchronize. When the PMSM is synchronized then there is no current induced in the damper windings since the slip is zero and then there is no asynchronous torque produced.

In a scalar controlled PMSM the stator currents are not controlled directly. A scalar controlled PMSM can become unstable easily especially when the load torque reaches the break down torque value.

Considering its disadvantages the scalar control is not suitable for low speed control of PMSM in high dynamic applications.

1.3.2 Vector control

Vector control offers superior performance when compared to scalar control. Vector control eliminates almost all the disadvantages of scalar control. The main idea of vector control is to control not only the magnitude and frequency of the supply voltages but also the angle.

With other words said the magnitude and angles of the space vectors is controlled. There are different kind of vector controls, the two most commonly used being DTC and FOC.

1.3.2.1 Direct torque control

Direct torque control was introduced on the market by ABB. The DTC has some advantages like simple control scheme, good dynamic response and it does not needs rotor speed or position feedback thus being considered a sensorless control technique.

The control scheme of classical DTC is much simpler than that of FOC as there is no reference frame transformation or position and speed measurement needed. The DTC scheme consists of torque and stator flux estimators, torque and flux hysteresis comparators a switching table and a voltage source inverter. The principle of DTC is to choose a voltage vector to control both stator flux and torque simultaneously. The stator currents and DC-link voltage are sampled and used in the flux and torque estimation. The estimated torque and flux magnitudes are compared with their reference values in the hysteresis comparators and then the outputs of the hysteresis comparators are feed to the switching table in order to select the appropriate voltage vectors in each sampling period (Paturca).

The drawbacks of classical DTC are high torque and current ripples during steady state operation unless operated at very high switching frequencies (40 KHz) which increases the overall cost of the drive system.

1.3.2.1 Field oriented control

The objective of field oriented control is to be able to control the PMSM as a separately excited DC machine meaning that the flux and torque can be controlled separately (in a decoupled way). The instantaneous stator currents are transformed to the dq rotating reference frame by means using mathematical equations and taking into account the rotor position. The flux is controlled through the d-axis current while the torque is controlled through the q-axis current. It is not enough to use only the dq transformation in order to achieve decoupled control of flux and torque since there is coupling between the two axes which may be canceled out by subtracting from the dq-axis reference voltages the appropriate coupling terms. Two types of field oriented control are possible for the PMSM: rotor oriented FOC and stator oriented FOC.

Due to its advantages like low torque and current ripple, constant VSI switching frequency, low audible noise FOC control scheme is chosen for further analysis.

1.4 PMSMs versus INDUCTION MACHINES

In contrast to the induction machines, the PMSMs do not require magnetizing component of stator current, since the excitation is provided by magnets in those machines.

This causes a reduction in stator copper loss in PMSMs. Moreover, the copper loss associated with rotor in induction machines does not exist in PMSMs. This copper loss reduction in stator and rotor significantly improves the efficiency in PMSMs compared to the induction machines. However, it should be mentioned that during flux weakening regime operation the PMSMs require high stator current to weaken the flux (Jahns, Leonhard) increasing the stator copper loss. This reduces the efficiency of PMSMs during flux weakening regime operation and both PMSMs and induction machines suffer with less efficiency characteristics in that regime operation. This implies that from efficiency point of view the PMSMs are well suited over the induction machines in the applications like pumps and fans, where the machines are operated in constant torque regime.

The growing electrical energy consumption is one of the major problems that world faces at present. Most of this electrical energy is consumed in motor drives and a large fraction of these motor drives consumed energy goes to the induction machine drives with pumps and fans (Flemming). Therefore, in pumps and fans drives, using PMSMs instead of using induction machines, it can be contributed to reduce the total electrical energy consumption significantly.

Another attractive feature of PMSMs over the induction machines is that the possibility of design them with less weight and volume. Recently, the IPMSMs were designed with significant reduction of weight and volume over the induction machines (Yaskawa, Sawa). Moreover, they also have high torque to inertia (Te/J) ratio, which is highly attractive for applications that demand fast dynamic response.

Since PMSMs are synchronous machines their control should always be incorporated with self synchronization concept as explained in section 1.3. It is not a requirement for induction machine control since they are asynchronous machines. This makes the main difference in control concepts for these two types of machines.

1.5 OBJECTIVE OF DISSERTATION

Modeling and simulation is usually used in designing PM drives compared to building system prototypes because of the cost. Having selected all components, the simulation process can start to calculate steady state and dynamic performance and losses that would have been obtained if the drive were actually constructed. This practice reduces time, cost of building prototypes and ensures that requirements are achieved.

In this work, the simulation of PMSM is developed using SIMULINK. The vector control is one of the high performance control strategies for ac machine. The simulation circuit includes all realistic components of the drive system.

The growth in the market of PMSM motor drives has demanded the need of simulation tool 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.

The aim of the project is to study the implementation of the vector control in Permanent Magnet Synchronous Motor (PMSM).

Specific objectives

1) Mathematical modeling of the intelligent power module based PMSM drive.
2) Prototype development of IPM based PMSM drive.
3) Investigation of IPM based PMSM drive under various balanced/unbalanced input output conditions.

1.6 ORGANIZATION OF THE DISSERTATION

The remainder of this dissertation is organized as follows:

Chapter 1 presents the general theory of permanent magnet synchronous motors (PMSM), with focus on different motor types and their control fundamentals. This chapter also presents the main benefits and drawbacks of various motor types and compares permanent magnet synchronous motor with induction motor.

Chapter 2 includes literature review collected from the different research papers of different authors on control theory of permanent magnet synchronous motor, different speed control methods, mathematical modeling and simulation of permanent magnet synchronous motor.

Chapter 3 presents the theory of the permanent magnet synchronous motor (PMSM), its construction details principle of operation and different starting methods. The chapter also presents different speed control methods and discusses various field oriented control (FOC) properties.

Chapter 4 gives a presentation of permanent magnet synchronous motor (PMSM) drive system and its classification.

Chapter 5 presents detailed modeling of permanent magnet synchronous motor (PMSM)**,** parks transformation and dynamic d q modeling, field oriented control of pm motors and speed control of pm motor.

Chapter 6 presents the vector controlled permanent magnet synchronous motor (PMSM) drive in MATLAB/SIMULINK. The chapter also presents the individual simulations and their results of the models.

Chapter 7 discusses the simulation result for various speed and load torque; also the results are analyzed and discussed.

Chapter 8 presents the experimental performance of IPM based PMSM. The chapter also presents the laboratory results which are discussed in brief.

Chapter 9 presents general conclusions and recommendations for future work.

1.7 CLOSURE

Thus, this chapter presented introduction and the basic theory of the project. This chapter covers classification of different permanent magnet motor and their control fundamentals. Benefits and drawbacks of various motor types are also discussed. It also includes objectives of the dissertation and brief outline of the thesis.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

A literature survey forms the basis on which a project can be built or developed. It forms the core to which ideas can be added and developed into a comprehensive system, which will be able to cover the deficiencies of some of the existing systems.

This chapter deals with the data and information accumulated after referring to many books, articles and technical papers written by well-known authors and the problem definition of the project.

2.2 LITERATURE SURVEY

PM motor drives have been a topic of interest for the last twenty years. Different authors have carried out modeling and simulation of such drives.
Some of the typical papers concerning this topic are listed below.

Slemon T. 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.
Pillay presented PM motor drives and classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BDCM 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 BDCM, it is also shown in this paper that no particular advantage exists in transforming the abc equations of the BCDM to the d, q frame.

Neumann, T.W. 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.

As an extension of his previous work, Pillay P. 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.

Morimoto S. in their paper aimed to improve efficiency in permanent magnet (PM) synchronous motor drives. The controllable electrical loss which consisted of the copper loss and the iron loss could be minimized by the optimal control of the armature current vector. The control algorithm of current vector minimizing the electrical loss was proposed and the optimal current vector could be decided according to the operating speed and the load conditions. The proposed control algorithm was applied to the experimental PM motor drive system, in which one digital signal processor was employed to execute the control algorithms, and several drive tests were carried out. The operating characteristics controlled by the loss minimization control algorithm were examined in detail by computer simulations and experimental results.

Wijenayake A.H. described the development of a two-axis circuit model for permanent magnet synchronous motor (PMSM) by taking machine magnetic parameter variations and core loss into account. The circuit model was applied to both surface mounted magnet and interior permanent magnet rotor configurations. A method for on-line parameter identification scheme based on no-load parameters and saturation level, to improve the model, was discussed in detail. Test schemes to measure the equivalent circuit parameters, and to calculate saturation constants which govern the parameter variations were also presented.

Jang Mok K. proposed a novel flux-weakening scheme for an Interior Permanent Magnet Synchronous Motor (IPMSM). It was implemented based on the output of the synchronous PI current regulator reference voltage to PWM inverter. The on-set of flux weakening and the level of the flux were adjusted inherently by the outer voltage regulation loop to prevent the saturation of the current regulator. Attractive features of this flux weakening scheme included no dependency on the machine parameters, the guarantee of current regulation at any operating condition, and smooth and fast transition into and out of the flux weakening mode. Experimental results at various operating conditions including the case of detuned parameters were presented to verify the feasibility of the proposed control scheme.

Bose B. K. 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 were 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 were given.

Bowen C. addressed the modeling and simulation of permanent magnet synchronous motor supplied from a six step continuous inverter based on state space method. The motor model was derived in the stationary reference frame and then in the rotor reference frame using Park transformation. The simulation results obtained showed that the method used for deciding initial conditions was very effective.

Mademlis C. presented an efficiency optimization method for vector-controlled interior permanent-magnet synchronous motor drive. Based on theoretical analysis, a loss minimization condition that determines the optimal q-axis component of the armature current was derived. Selected experimental results were presented to validate the effectiveness of the proposed control method.

Jian Xin X. applied a modular control approach to a permanent-magnet synchronous motor (PMSM) speed control. Based on the functioning of the individual module, the modular approach enabled the powerfully intelligent and robust control modules to easily replace any existing module which did not perform well, meanwhile retaining other existing modules which were still effective. Property analysis was first conducted for the existing function modules in a conventional PMSM control system: proportional-integral (PI) speed control module, reference current-generating module, and PI current control module. Next, it was shown that the conventional PMSM controller was not able to reject the torque pulsation which was the main hurdle when PMSM was used as a high-performance servo. By virtue of the internal model, to nullify the torque pulsation it was imperative to incorporate an internal model in the feed-through path. This was achieved by replacing the reference current-generating module with an iterative learning control (ILC) module. The ILC module records the cyclic torque and reference current signals over one entire cycle, and then uses those signals to update the reference current for the next cycle. As a consequence, the torque pulsation could be reduced significantly. In order to estimate the torque ripples which might exceed certain bandwidth of a torque transducer, a novel torque estimation module using a gain-shaped sliding-mode observer was further developed to facilitate the implementation of torque learning control. The proposed control system was evaluated through real-time implementation and experimental results validated the effectiveness.

Ong C. explained the need for powerful computation tools to solve complex models of motor drives. Among the different simulation tools available for dynamic simulation he had chosen MATLAB/SIMULINK® as the platform for his book because of the short learning curve required to start using it, it's wide distribution, and its general purpose nature.

Araujo R.E. mentioned the different simulation tools available and the benefits that were obtained by accelerating the process for the development of visual design concepts. Among various software packages for simulation of electronic circuits, like SPICE and SABER, EMTP, EUROSTAG, or for specialized simulations tools for power electronics system like SIMPLORER, POSTMAC, SIMSEN, ANSIM, and PSCAD, they had chosen MATLAB/SIMULINK. MATLAB/SIMULINK had user-friendly environment, visual design, Real-Time Workshop and libraries of model for the various components of a power electronic system.

Macbahi H. mentioned that a great number of universities and researchers used the MATLAB/SIMULINK software in the field of electrical machines because of its advantage such as user friendly environment, visual oriented programming concept, non-linear standard blocks and a large number of toolboxes for special applications.

Reece J.H. discussed three possible computer simulation tools such as PSpice, HARMFLO and the Electromagnetic Transients Program (EMTP) in their project on power systems containing adjustable speed drives. They selected EMTP as the primary simulation tool because of its broad range of capabilities, which were well matched to their problem.

French C.D. had found that in recent years the increase in desktop computing power has lead to an increase in the sophistication of both design and simulation tools available to the design engineer. One such tool becoming more wide spread amongst academia and industry was Math work’s SIMULINK / MATLAB package. This paper described how SIMULINK could be used as an integrated development environment for simulation and real time control of electric motor drive systems. This was carried out with the aid of motor models together with simulation and real time control circuits. It was demonstrated how such a set-up could be used as a cost effective control system rapid prototyping scheme.

Onoda S. had developed a modeling tool to study automotive systems using the power electronics simulator (PSIM) software. PSIM was originally made for simulating power electronic converters and motor drives. This user- friendly simulation package was able to simulate electric/electronic circuits.

Venkaterama G. had developed a simulation for permanent magnet motors using MATLAB/SIMULINK. The motor was a 5 hp PM synchronous line start type. Its model included the damper windings required to start the motor and the mathematical model was derived in rotor reference frame. The simulation was presented with the plots of rotor currents, stator currents, speed and torque.

Stulrajter Marek presents different approaches of pmsm control strategies. Scalar control and vector control were chosen as possible methods for ac motors control. Theoretical background briefly describes the properties of these control techniques. Several advantages and disadvantages are highlighted and confirmed by simulations.

SIMULINK PM Synchronous Motor Drive demo circuit used the AC6 block of Sim Power Systems library. It modeled a permanent magnet synchronous motor drive with a braking chopper. The PM synchronous motor was fed by a PWM voltage source inverter, which was built using a Universal Bridge Block. The speed control loop used a PI regulator to produce the flux and torque references for the vector control block. The vector control block computed the three reference motor line currents corresponding to the flux and torque references and then fed the motor with these currents using a three-phase current regulator. Motor current, speed, and torque signals were available at the output of the block.

The demo circuit in SIMULINK for Permanent magnet synchronous motor fed by PWM inverter had a three-phase motor rated 1.1 kW, 220 V, 3000 rpm. The PWM inverter was built entirely with standard SIMULINK blocks. Its output went through Controlled Voltage Source blocks before being applied to the PMSM block's stator windings. Two control loops were used. The inner loop regulated the motor's stator currents. The outer loop controlled the motor's speed. Line to line voltages, three phase currents, speed and torque were available at the output of the scope blocks.

Zhong L. presents and describes an investigation of DTC for Permanent magnet synchronous motor (PMSM) drives. The Analysis of PMSMs shows that the increase of electromagnetic Torque is proportional to the increase of the angle between the Stator and rotor flux linkages and therefore fast torque response can be obtained by increasing the rotating speed of the stator flux Linkage as fast as possible. The implementation of DTC in PMSM Drives is discussed and the switching table specific for an interior PMSMs is derived. The proposed control is implemented on a Prototype PMSM, which has a standard induction motor stator, and the experimental results show that the torque response is extremely fast. It is also demonstrated that the position sensor is not essential for the inner torque control loop of PMSM drives with DTC.

Prasad E. presents the principle of space vector pulse width modulation (SVPWM) was introduced and implementing for PMSM. Applying SVPWM technique to the PMSM and obtaining the speed, torque, current Responses when load was increased. The Mathematical model of PMSM is analyzed by Neglecting the saturation of the electric motor Ferrite core, turbulent flow and hysteresis loss in electric motor. Assuming that the current in the electric motor is symmetrical three Phase sinusoidal current and the system model of FOC vector control has-been Established. The control system has been simulated by MATLAB/SIMULINK. Simulation results show that the model is Effective, and the method provides a frame of reference for software and hardware designs.

Konghirun Mongkol present and describe that the rotor position is necessary to achieve the vector control drive system of Permanent Magnet Synchronous Motor (PMSM). In this paper, the resolver sensor detecting the rotor position of PMSM is focused. The outstanding features of this sensor are its robust structure and noise insensitivity. The resolver algorithm is proposed and implemented in the vector control drive system of PMSM. The proposed scheme has been varied by both simulation and experiment using MATLAB/SIMULINK and the TMS320F2812 based digital controller, respectively.

Youn Myung Joong presented a current control technique for a permanent magnet synchronous motor (PMSM) with a simple disturbance estimation scheme is proposed. Among the various current control schemes for a PMSM Drive, the predictive control is known to give a superior performance. This scheme, however, requires the full knowledge of motor parameters. To overcome such a limitation, the disturbances caused by the parameter Variations will be estimated by using a disturbance observer theory and used for the calculation of the reference voltages by a feed forward Control. Thus, the control performance can be significantly improved with a relatively simple control algorithm.

Li Shihua presents the speed-regulation problem for permanent magnet synchronous Motor (PMSM) system under vector control framework is studied. For the speed loop, a standard internal model controller is first designed based on a first-order model of PMSM by analyzing the Relationship between reference quadrature axis current and speed. Considering the disadvantages that the standard imc method is sensitive to control input saturation and provides a poor Load disturbance rejection performance, a modified imc is introduced where a feedback control term is added to form a composite control structure. For the two current-loops, pi algorithms are employed respectively. Simulation and experimental results show the effectiveness of the proposed control method.

Consoli Alfio presents the state of the art in the area of industrial applications of sensor less control for permanent-magnet Synchronous motor (PMSM) drive. A new emerging technology is becoming mature to come to the market, based on high-frequency Signal injection that makes it possible to achieve zero-speed operation without increasing the complexity and the cost of the system. After an overview of major theoretical principles of sensor less control of PMSMs, the paper focuses on the practical implementation of one of the previously described high-frequency injection techniques in both salient and non salient pm machines. Experimental results are presented, including useful hints for practical implementation.

Singh Rahul presents and describe that Permanent Magnet Synchronous Motor are used in many applications that require rapid torque response and high performance operation. New developed materials such as magnetic materials, conducting materials and insulating materials as well as several new applications have greatly contributed to the development of small and special purpose machines. Using such materials the size of the motor would considerably reduce and high performance motors can be built. Due to several new applications these motors are quite popular in a developing country such as india. The speed of a permanent magnet synchronous motor is varied by varying the frequency of an inverter. The performance of the motor is experimentally verified and the results are found to be encouraging. It is also observed that, under varying load condition, the speed of a motor remains constant at constant frequency.

Abdel rady ibrahim mohamed Yasser presents a novel direct instantaneous torque control Scheme for a direct drive (dd) permanent magnet synchronous motor (pmsm) is presented. 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 can be obtained with the proposed Cascaded control structure. To robustly 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. Experimental results are presented to demonstrate the validity and effectiveness of the proposed instantaneous torque control scheme.

Rasmussen H. presents a simple control method for controlling Permanent magnet synchronous motors (PMSM) in a wide speed Range without a shaft sensor. The method estimates the stator flux by integration of the measured emf signal. To compensate for the offset in the bemf the offset is estimated. The control method is made robust at zero and low speed by changing the direct vector current component to a value different from zero. In order to verify the applicability of the method the Controller has been implemented and tested on an 800 w motor.

Fuentes Esteban J. presents a predictive strategy for the Speed control of a two-mass system driven by a permanent magnet Synchronous motor (PMSM). The proposed approach allows manipulating all the system variables simultaneously, including mechanical and electrical variables in a single control law. The state Feedback is achieved with a reduced order extended kalman filter, which observes the non-measured variables as well as reduces the Impact of measurement noise. The performance of the control Strategy is shown through simulation and experimental results in a [4 kW] laboratory prototype.

Solsona Jorge presented paper introduces a sensor less nonlinear control Scheme for controlling the speed of a permanent magnet Synchronous motor (pmsm) driving an unknown load torque. The states of the motor and disturbance torque are estimated via an extended nonlinear observer avoiding the use of mechanical Sensors. The control strategy is an exact feedback linearization Law, with trajectory tracking evaluated on estimated values of the PMSM states and the disturbance torque. The system Performance is evaluated by simulations.

Wallmark Oskar presents analytical expressions for the converter Input admittance in field-oriented controlled permanent magnet Synchronous motor (PMSM) drives. The effect of rotor Saliency is taken into consideration and the derived admittance

Expressions are valid for maximum-torque-per-ampere as well as High-speed (field weakening) operation. Experimental results illustrate the validity of the derived admittance expressions. The presented Work can be used to predict dc-link voltage instabilities in PMSM drives in, e.g., railway traction, aerospace and automotive applications.

Perera Chandana P. D. presented that when permanent-magnet synchronous motors (PMSMs) are used for pump and fan applications, v/f control Methods can be used to control them. The problem with open-loop v/f control of PMSMs without having damper windings in the Rotor is the inherent instability after exceeding a certain applied Frequency. In this paper, a new v/f control method is proposed for motor drives for stable operation in a wide frequency range. The magnitude of the voltage is controlled in order to maintain a Constant stator flux linkage in the pmsm. The applied frequency is modulated proportional to the input power perturbations to stabilize the drive for a wide frequency range. No position sensor is required to implement this stabilizing technique. The small-signal Analysis and the experimental results confirm the effectiveness of this stabilizing technique. The experimental results also indicate the satisfactory performance of the drive for pump and fan applications.

Tiwari nath Amar presents modeling; controller design and simulation of a PMSM drive. Hysteresis current controller issued for inner loop current control and pi controller for outer loop speed control. A simplified closed loop Transfer function has been developed for the proposed drive and complete controller algorithm is given. The Stability of the controller is studied for variations in the drive inertia and mechanical damping. The simulation Results are shown for the verification of the controller algorithm.

Yan Ying presents the direct torque controlled (DTC) permanent magnet Synchronous motor (PMSM) drive has become competitive compared with other types of drive systems because of its simple and sensor less control algorithm. The application of the system, however, is handicapped by the difficulty of starting under full Load due to the unknown initial rotor position. This paper presents a nonlinear model of PMSMs which incorporates both the structural and saturation saliencies to enable the numerical Simulation of initial rotor position detection algorithms. In this Model, the phase inductances are expressed by Fourier series as functions of the stator current and rotor position. The Inductances of a surface mounted PMSM is measured with Different rotor positions and dc offset currents, which emulate the effect of the three phase stator currents. By using the proposed model, the DTC PMSM is simulated and the results are compared with those obtained by the PMSM model in the SIMULINK library. With the model, an initial rotor position Estimation scheme using voltage pulses is investigated by Numerical simulation. The scheme is also experimentally tested and the results are compared with the inductance variation to verify the validity of the method. The effectiveness of the scheme to estimate the initial rotor position for the testing PMSMs is Analyzed and verified by numerical simulation before physical Implementation.

Cavallaro Calogero presents a new loss minimization control algorithm for inverter-fed permanent-magnet synchronous motors (PMSMs), which allows for the reduction of the power losses of The electric drive without penalty on its dynamic performance, is Analyzed, experimentally realized, and validated. In particular, after a brief recounting of two loss minimization control strategies, namely, the “search control” and the “loss-model control,” both a new modified dynamic model of the PMSM (which takes into Account the iron losses) and an innovative “loss-model” control Strategy are presented. Experimental tests on a specific PMSM Drive employing the proposed loss minimization algorithm have been performed, aiming to validate the actual implementation. The Main results of these tests confirm that the dynamic performance of the drive is maintained, and in small motors enhancement up To 3.5% of the efficiency can be reached in comparison with the PMSM drive equipped with a more traditional control strategy.

Harnefors Lennart presented proposes control algorithms for a fault tolerant Permanent-magnet synchronous motor (PMSM) drive. In order to improve the reliability of the drive, an algorithm for Achieving a sensor less control that operates properly also in fault Mode is proposed. Furthermore, it is shown how a closed-loop Field-weakening controller needs to be modified in order to operate properly in fault mode. Automotive applications are in mind and the algorithms presented are verified with experimental results using an in-wheel PMSM. With the proposed modifications, the Reliability of the drive can be improved. In the above works, none of them have considered a real drive system simulation in SIMULINK operating at constant torque and flux weakening regions.

Rao J. Sinivas presents the direct torque control (DTC) requires low Computational power when implemented digitally for ac Drives. The DTC possess good dynamic performance but Shows quite poor performance in steady-state since the Crude voltage selection criteria give rise to high ripple Levels in stator current, flux linkage and torque. To reduce the problems with DTC the discrete space vector modulation Method is proposed for DTC by applying more vectors in one Interval. In this paper, after a brief review of the primary Concept of DTC technique, a new scheme of DSVM DTC for pmsm is proposed with a new set of switching tables. Simulation On the proposed scheme is carried out and compared with basic DTC scheme.

Ameur A. presents a speed senso rless direct torque Control scheme using space vector modulation (DTC-SVM) for Permanent magnet synchronous motor (PMSM) drive based a model Reference adaptive system (mras) algorithm and stator resistance Estimator [39]. The mras is utilized to estimate speed and stator Resistance and compensate the effects of parameter variation on stator Resistance, which makes flux and torque estimation more accurate and insensitive to parameter variation. In other hand the use of SVM method reduces the torque ripple while achieving a good dynamic Response. Simulation results are presented and show the effectiveness of the proposed method.

Zhu Jianguo presents conventional switching-table-based direct torque Control (DTC) presents large torque and flux ripples as well as Variable switching frequency. Many methods have been proposed to tackle the aforementioned problems, among which duty cycle Control is a kind of very effective approach. It is known that by adjusting the duty ratio of the active vector selected from the switching Table, the torque ripple can be reduced. However, most of the Prior duty cycle control methods only focus on the torque performance Improvement and fail to take the flux ripple reduction into Account. Furthermore, the method obtaining the duty ratio is usually complicated and relies heavily on the accuracy of machine Parameters, which negates the merits of simplicity and robustness of conventional DTC. This paper proposes a unified switching table to select three vectors rather than two vectors in prior arts; hence, lower flux ripple and more sinusoidal stator current can be obtained while maintaining the torque performance. A very simple but effective method is proposed to obtain the durations of the three vectors. The influence of one-step delay caused by digital implementation is investigated. By arranging the switching sequence of the three vectors appropriately, the switching frequency can be significantly reduced. The superiority of the novel method is confirmed by a comparative study with its counterpart using two Vectors only. Both simulation and experimental results obtained from a 1-kw permanent magnet synchronous motor (PMSM) DTC Drive are presented to validate the effectiveness of the novel duty Cycle control strategy.

Juan C. Balda presents and describes the classical techniques such as the root locus, Bode plots and Nyquist diagrams are used for designing fixed structure speed controllers for ac drives, the design would normally be done around a nominal value of the controlled plant. Generally, a sensitivity analysis would subsequently be done to ensure that the design specifications are met when the plant parameters change. This procedure can and has worked well. In this paper an alternative is proposed where the parameter variations are included at the outset of the design task. The Nichols chart lends itself rather well to this application since it represents both magnitude and phase information on a single diagram. By using this alternative, it may be possible to reduce the overall time needed to complete the design. The particular technique is called quantitative feedback theory (QFT) which is used in conjunction with the Nichols chart. This paper presents the basics of QFT and shows how it can be used for the design of fixed-structure controllers for parameter-sensitive plants in conjunction with the Nichols chart. A design is presented and verified experimentally.

2.3 CLOSURE

Exhaustive literature survey has been attempted to study different speed control methods of permanent magnet synchronous motor (PMSM). Brief literature review collected from the different research papers of different authors has been presented.

CHAPTER 3

THEORETICAL ANALYSIS OF PERMANENT MAGNET SYNCHRONOUS MOTOR

3.1 INTRODUCTION

Permanent magnet synchronous motors are increasing applied in several areas such as traction, automobiles, robotics and aerospace technology. The power density of permanent magnet synchronous motor is higher than one of induction motor with the same ratings due to the no stator power dedicated to the magnetic field production. Nowadays, permanent magnet synchronous motor is designed not only to be more powerful but also with lower mass and lower moment of inertia.

3.2 COMMON MOTOR TYPES IN MOTION CONTROL

The first speed-controlled drive was introduced over 100 years ago by Harry Ward Leonard in his paper "Volts versus ohms – speed regulation of electric motors". The rotating rectifier consisted of a grid-supplied induction machine that rotated a DC generator. By adjusting the magnetization of the DC generator, controllable DC voltage was available for the speed control of a DC motor.

Although three machines were required, it was at the time the only possibility to realize a speed controlled drive. When the transistors and first micro-processors were introduced, chopper technologies such as the PWM enabled the accurate speed control of DC machines. Brushless DC motors with permanent magnets in the rotor were also introduced in the early 1960s, but since there were not powerful enough PM materials available yet, their power range was limited typically below 10 kW. Typical applications for brushless DC motors were small machine tools, tape recorders, and robotics. For higher-power speed-controlled applications, brushed DC motor was for a long time the only solution. Until the early 1980s, when high energy density NdFeB magnets were introduced, it was possible to get rid of the brushes also at the higher power range up to hundreds of KWs by using a brushless DC motor. Later on, the introduction of the field oriented control for machines made it possible to use AC machines in demanding speed controlled applications. First, the speed-controlled AC drives were induction motor drives, but as the vector control for PMSMs was introduced in the early 1990s, they soon started to gain ground from the DC motors and have dominated in the motion control industry ever since. The trend in the motion control nowadays is clearly towards the brushless AC machines with sinusoidal excitation, which, in practice, means that a permanent magnet synchronous motor or an induction motor must be used.

It can be concluded that the brushed DC motors dominated the speed controlled drives in the 1960s and 70s, and the brushless DC motors in the 1980s. Since the early 1990s, PMSMs have dominated the motion control industry to the present, and, according to the current trend, there seems to be no end for that. Induction motors have always been a minority in the motion control, and they are mainly used in applications, where the field weakening can be utilized to avoid the over-sizing of the drive, which would be the case with PMSMs. The most common motor types are presented below.

3.2.1 BRUSHED DC MOTOR

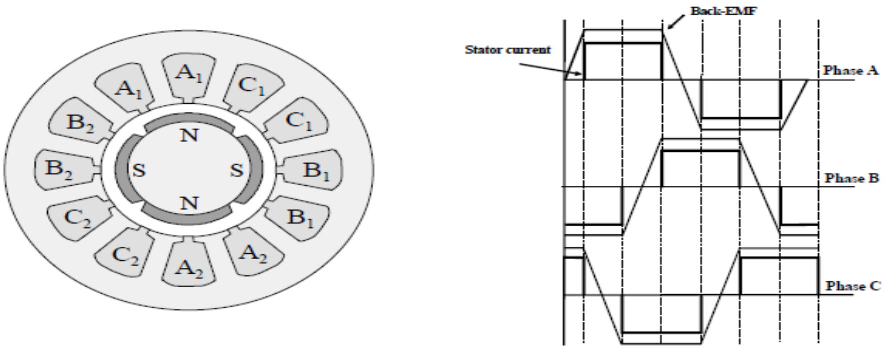
DC motor was for a long time the only motor type available to convert electrical power into mechanical power, and due to its straightforward operating characteristics and simple and stable control, it is still being used to some extent in speed-controlled applications. The speed of the motor is controlled by controlling the armature voltage, and the torque by the armature current, that is, the flux and the torque can easily be controlled separately. This is the main principle on which all the modern AC control methods nowadays rely. The first DC motors were controlled with some chopper technology, such as the pulse width modulation (PWM). Network-connected thyristor bridges were mainly used in higher power range, typically in a variety of applications such as in printing and paper industry, passenger lifts, and any kinds of drives subjected to high transient loading, such as in rolling mills. Chopper technology was mainly used in the lower power range, such as in machine tool applications. Development in permanent magnet materials introduced a permanent magnet DC (PMDC) motor, in which the stator excitation coil was replaced by permanent magnets. Some advantages in using permanent magnet excitation were decreased copper losses, higher power density, and a smaller torque ripple at low speeds. Using permanent magnet material in the magnetic circuit causes a low armature inductance and hence a low armature reaction. An extremely linear speed-torque characteristic of the motor, which result from the permanent magnet-provided constant field flux at all speeds, makes the control of the PMDC very straightforward; the speed of the motor is controlled by simply adjusting the armature DC voltage. PMDC machines were, however, limited to the lower power range due to the absence of the proper magnets until the 1980s. Typical applications of PMDC were low voltage battery powered applications, such as machine tools, automotive auxiliary drive applications, and solar powered applications. Above the 10 kW range, the separately excited DC motor was the only solution, as it provided high dynamic performance especially when fully compensated.

Although the separately excited DC motor suits extremely well to servo applications thanks to its dynamic performance, the major problem is the mechanical commutator and the carbon brushes, which require regular maintenance. The commutator also degrades the overloading capability of the machine. Good commutation, which means armature current reversal in a single armature coil without sparking at the brushes, is extremely important to prevent the premature brush failure.

There is a physical limit to the speed and to the power, at which the current can be commutated. This limit is often expressed as a product of the mechanical power and speed; a widely accepted value for this product is 3 TW/min (Drury). If this limit is excessively exceeded, a ring of heavy sparking runs around the commutator circumference. This is known as a brush fire or a brush flashover, and it will rapidly destroy the brushes and the commutator. If the commutation limit has to be exceeded, several armatures on a single shaft are required, which makes the drive more complex and expensive. There still are numerous applications, in which the most demanding motion control is realized with a brushed DC motor, because when properly maintained, the DC motor has a dynamic performance equal to the modern vector controlled AC drive with a notably simpler control. Therefore it is not surprising that even today, in the literature, the word “servo motor” often refers to a brushed DC motor.

3.2.2 BRUSHLESS DC MOTOR (BLDC)

A brushless DC motor (BLDC), introduced in 1962 by T.G.Wilson and P.H.Trickey in “DC Machine with Solid State Commutation” (Wilson 1962), has a classic three-phase stator, and the rotor has surface magnets that produce rectangular air gap flux distribution. The stator may have a distributed or a concentrated winding, although the latter one is more often preferred. The motor is driven by rectangular or trapezoidal voltage strokes coupled with the given rotor position. The voltage strokes must be properly applied between the phases, so that the angle between the stator flux and the rotor flux is kept close to 90° to get the maximum generated torque. The position sensor required for the commutation can be very simple, since only six pulses per revolution (in a three-phase machine) are required. Typically, the position feedback is comprised using three Hall Effect sensors aligned with the back-EMF of the motor. Figure 1.5 a) shows the geometry of the machine and b) the stator current- and the back-EMF waveforms.



a)

b)

Figure 3.1: The geometry and the operating principle of the BLDC motor. a) Four-pole brushless DC motor with three-phase concentrated winding. b) Phase-current and back-EMF waveforms in an ideal case. In a real motor, the switching of the stator current between the phases is never simultaneous, which easily causes significant torque ripple with this motor type.

According to Crowder, with equal air gap peak flux densities and equal RMS currents, a BLDC can produce 47 % more torque than a comparable PMSM with sinusoidal air gap flux density distribution. This is because both the average flux density in one pole area and the RMS value of the current will be higher with the BLDC because of the rectangular air gap flux density and the stator current distribution. Of course, in order to produce a rectangular flux distribution in the air gap, a BLDC requires more PM material in the rotor. If the amount of PM material in both machines is chosen equal, the PMSM produces slightly higher torque with equal RMS current than the BLDC (Crowder).

Although the control principle and the construction of the converter power stage of the BLDC motor are relatively simple, high torque ripple is generated even by small delay errors in the commutation, when the square wave current is switched from one the phase to another. With real switches, the commutation requires always a finite time, which can be seen in the torque ripple. More torque ripple is generated if either the current or the back-EMF waveform deviates from rectangular, or if the currents in each phase differ by the amplitude. The torque ripple of BLDC machines is their biggest drawback; as a result, this motor type is often used in high-speed and high-inertia applications, where the mechanics of the system effectively filter the high-frequency ripple out. If a smooth torque at lower speeds is required, AC motors with sinusoidal excitation are commonly preferred, which often leads to the selection of a permanent magnet synchronous motor.

3.2.3 PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM)

In principle, the construction of a permanent magnet synchronous machine does not differ from that of the BLDC, although distributed windings are more often used. However, while the excitation current waveform was rectangular with a BLDC, sinusoidal excitation is used with PMSMs, which eliminates the torque ripple caused by the commutation. PMSMs are typically fed by voltage source inverters, which cause time-dependent harmonics on the air gap flux. Permanent magnet synchronous machines can be realized with either embedded or surface magnets on the rotor, and the location of the magnets can have a significant effect on the motor’s mechanical and electrical characteristics, especially on the inductances of the machine. As the relative permeability of the modern rare-earth magnets, such as the NdFeB is only slightly above unity, the effective air gap becomes long with a surface magnet construction. This makes the direct-axis inductance very low, which has a substantial effect on the machine’s overloading capability, and also on the field weakening characteristics. As the pull-out torque is inversely proportional to the d-axis inductance, the pull-out torque becomes very high. Typically, the per unit values of the d-axis synchronous inductances of the SMPMSM servos vary between 0.2–0.35 p.u., and consequently the pull-out torque is in the range of 4–6 p.u., which makes them well suitable in motion control applications.

The drawback of a low Ld – value is the very short field weakening range, as the armature reaction with a surface magnet construction is very weak. This means that a high demagnetizing stator current component would be required to decrease the air gap flux, and consequently, there would be very little current left on the q-axis to produce the torque. Direct-axis inductance of a machine having embedded magnets becomes high, as the rotor magnets per pole form a parallel connection for the flux, while with a surface magnet construction they are connected in series. With equivalent magnets, the rotor reluctance of the surface-magnet construction is therefore double compared to an embedded-magnet construction, and the inductance is inversely proportional to the reluctance. With embedded-magnets, the direct-axis inductance is further increased because of the higher rotor leakage flux. Three basic configurations of PMSMs are shown in Fig. 3.2.

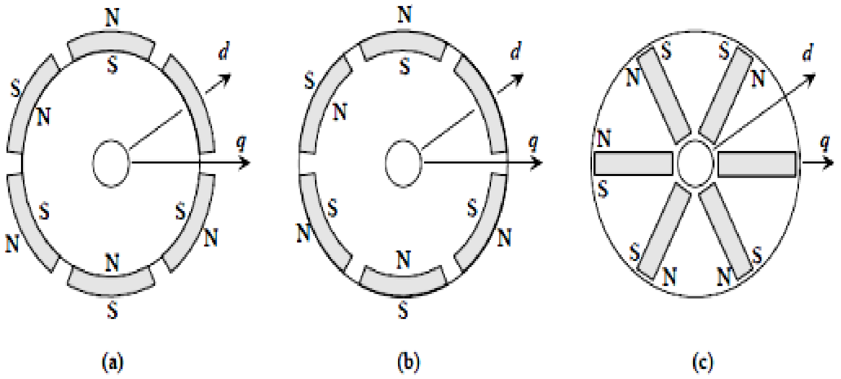


Figure 3.2: The most common PM rotor constructions. a) Non-salient surface magnet rotor. Due to high d axis reluctance, Ld is low and consequently the pull-out torque high. b) Salient pole surface magnet rotor with inset magnets, which is basically the same as a), but this type produces also some reluctance torque. c) Embedded magnets in the rotor, which has a high Ld value, and consequently a poor overloading capability, but a lot better field weakening characteristics than with the surface magnet constructions.

Typically the construction of the PMSM servomotor is somewhere between a) and b), and the q-axis inductance is larger. Industrial PMSMs often represent the type c).

In addition to the good overloading capability, another reason that makes the surface magnet construction favorable in servo applications is the lower inertia. With multi-pole machines, the rotor and the stator yokes can be made very thin, and all the additional iron can be removed from the rotor to provide a lower inertia. These large holes also improve the heat transfer from the rotor, as the high frequency flux pulsations generate heat on the magnets and on the rotor iron. As the servomotors must typically rotate very fast, gluing does usually not suffice in attaching the magnets on the surface of the rotor, and some non-magnetic material, such as a stainless steel cylinder or a fiber-glass band must be used to support the magnets. The problem in using steel is that it is a highly conductive material, and the air gap harmonics strongly generate losses and consequently heat in it. Therefore, a fiber-glass band or a plastic cylinder is more often used for the magnet retaining. Unfortunately, electrical insulators are also thermal insulators, which mean that their thermal conductivity for the heat generated in the rotor iron and in the magnets is poor. The temperature rise of the magnets decreases their remanence flux density, and consequently the torque production. The rotor in Fig. 3.2 b) with inset surface magnets has better mechanical characteristics, but on the other hand, it has higher leakages between two adjacent magnets. In addition to the higher leakage, the torque production decreases more as the motor must operate at higher pole angle due to increased q-axis inductance compared to a non-salient rotor. Typically, the construction of commercial servomotors is somewhere between a) and b) in Fig. 3.2, that is, the magnets are slightly embedded in the rotor. This improves the mechanical strength of the rotor and introduces a reluctance difference-based term in the torque. According to measurements made at LUT for eight different commercial servomotors in the power range of 3–5 kW, the values for the q-axis inductances were 10–20 % higher than the values in the d-direction.

With buried magnets and flux concentration, a sinusoidal air gap flux density distribution is possible with simple rectangular magnets. A sinusoidal air gap flux distribution significantly decreases the cogging torque especially with low-speed multi-pole machines that have a low number of slots per poles per phase number q. Also, it is possible to increase the air gap flux density beyond the remanence flux density of the magnets with a flux concentration arrangement, and the machine can produce more torque at a given volume. This is especially desirable in low speed applications, such as in wind generators and in propulsion motors where the space is limited. As the direct-axis inductance is typically high with a buried magnet construction, the overloading capability will be poor, which makes this motor type incompetent in motion control applications. Typically, the embedded v-shape magnet machine can have Ld approx. 0.7 p.u, which means only 1.4 p.u. overloading capability according to the load-angle equation of a synchronous machine with the assumption that EPM = us = 1 p.u. and Ld = Lq. If there is a reluctance difference in the machine, the maximum torque can be somewhat larger. It must, however, be borne in mind that despite the embedded magnets, it is of course possible to increase the physical air gap large enough, and thereby to decrease the direct axis inductance of the machine remarkably from the value given above. However, the consumption of the magnet material is increased remarkably in such a case.

3.2.4 INDUCTION MOTOR

Induction machines are by far the largest group of all industrial electrical machines, converting approximately 70–80 % of all electrical energy into mechanical form. It has a very robust rotor construction, which makes it suitable for high-speed applications, and further, with a proper design, it can have good overloading and field weakening characteristics. The theory of induction machines is old and well-known, and therefore, both motors and inverters are widely available from numerous manufacturers from fractional kW machines up to MW range. The induction motor is also known as the asynchronous motor, which derives from the fact that the rotor is always lagging the stator magnetic field. The difference is called the slip, and it is a fundamental characteristic in the operation of an induction motor. The slip is problematic in drives where a high dynamic performance is required, as it degrades the transient response of the motor for instance during stepwise loading variations. Also the rotor copper losses are directly proportional to the slip. The slip can be decreased by reducing the rotor resistance, and also by using a higher air gap flux density.

The biggest drawback of the induction machine is the always lagging power factor, because the machine is magnetized from the stator, in other words, there is a magnetizing current flowing in the stator winding even at no-load conditions. This means that less torque is available with a given current than for example with a PMSM, or alternatively, more current is required to produce an equal torque, which leads to an inverter with a higher current rating. With four-pole industrial induction machines, the power factor typically varies between 0.8–0.9, but with low-power induction machines, it can be notably lower. The power factor of an induction machine is directly connected to the magnetizing inductance Lm (Vogt).

$$\cos(\varphi)\ \alpha\ L_m = \frac{E_m}{\omega_s I_m} = \frac{E_m m \xi_1 N 2\sqrt{2}}{\omega_s \Theta_{tot} \pi p} \qquad 3.1$$

where φ is the phase-angle, E_m the induced phase-voltage, m the phase number, ξ_1 the fundamental winding factor, N the number of turns, ω_s the stator angular frequency, I_m the RMS magnetizing current, Θ_{tot} the magneto-motive force and p the number of pole pairs. With PMSM servomotors, the number of pole pair's p is often chosen to be 3 or 4, as it is possible to use a rotor with a larger diameter in a given frame. This is because the stator yoke can be made thinner, as the number of pole pairs increases. The limiting factor in choosing the number of the pole-pairs with PMSMs is typically the leakage flux between two adjacent magnets. The increased rotor diameter can be seen in an increased output torque, and also on the amount of the copper, as a higher p leads to relatively shorter end windings. Consequently, the resistance and the mass of the motor slightly decrease. Although the same applies, in principle, also to the induction machines, increasing the pole-pair number introduces a problem, as the magnetizing inductance decreases according to Eq. (3.1). This can be explained by the fact that as the p increases, the share of the air gap reluctance from the entire flux path reluctance per pole increases, in other words, the air gap reluctance becomes more and more dominant with an increasing p. The power factor of the induction machines is therefore inversely proportional to the pole number squared

$$\cos(\varphi)\alpha \frac{1}{(2p)^2} \qquad 3.2$$

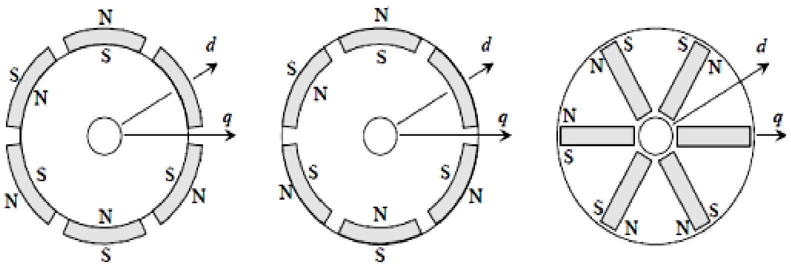
With PMSMs, it is also possible to use higher flux densities than with IMs, as the slight saturation does not affect significantly on the machine characteristics. This is convenient, as the output torque of electrical machines is proportional to the air gap flux density squared. A PMSM with a high air gap flux density also requires less stator current to produce the given torque, which means that there is a trade-off between the copper and the permanent magnet material. A lower stator current effectively decreases the stator copper losses, which are proportional to the current squared. This can have a significant effect on the thermal dimensioning of PMSMs, and could explain for instance why most commercial PMSM servos are fully closed with no integrated fan on the shaft. Induction servomotors are typically through-blown and thereby require a separate fan on the non-drive end. Using a high air gap flux density with induction machines to improve the performance introduces a problem, as the permeability of the iron decreases rapidly when the iron core starts to pass into saturation. This increases the magneto-motive force, and can be seen in the decreased magnetizing inductance according to Eq. (3.1). An increased magnetizing current can be seen in increased copper losses, and also iron losses are increased, as they are proportional to the flux density squared.

These problems can be partially solved, if the flux of the induction motor is dynamically adjusted as a function of the loading torque. For example, in a load cycle, a high air gap flux density is applied during the acceleration to provide the required overloading torque, and during the constant speed phase, the flux density is decreased to decrease the stator current and the losses of the machine. If the motor is dimensioned to operate at heavy saturation, decreasing the flux density back to the linear region of the BH curve can have a substantial effect on the magnetizing current. When driving the motor with a decreased flux, the torque decreases proportionally to the flux density squared. This significantly reduces the transient response of the motor for instance when a torque stroke occurs on the shaft. Too low a flux level could therefore cause the motor to stall if the load torque exceeds the pull-out torque. Basically, this means that it is necessary to know the instant at which the loading variation takes place, or in general, the load cycle has to be known in order to utilize the dynamic flux control with induction motor. With a proper design, also the overloading capability of an induction motor can be increased close to the values of surface magnet PMSMs. Since such a design inherently leads to good field weakening characteristics, an induction motor can be a respectable choice also in motion control applications.

3.3 BASIC CONSTRUCTION DETAILS OF PERMANENT MAGNET SYNCHRONOUS MOTOR

A PMSM consists of a magnetic rotor and wound stator construction. Its wound stators can rapidly dissipate heat to the motor housing and environment. In contrast, a brush motor traps the heat under a non-conductive air gap, resulting in greater efficiency and power density for the PMSM design and providing high torque-to-inertia ratios. A PMSM motor generates magnetic flux using permanent magnets in the rotors, which are driven by the stators applying a synchronous rotational field. On the other hand, the flux that is applied by the stators (the armature-reaction flux) generates torque most effectively when it is perpendicular to flux generated by the rotors. To maintain near-perpendicularity between stator flux and rotor flux, two control methods with position-speed feedback loop are popularly used for controlling a PMSM: Field-Oriented Control and Brushless DC Control.

In principle, the construction of a permanent magnet synchronous machine does not differ from that of the BLDC, although distributed windings are more often used. However, while the excitation current waveform was rectangular with a BLDC, sinusoidal excitation is used with PMSMs, which eliminates the torque ripple caused by the commutation. PMSMs are typically fed by voltage source inverters, which cause time-dependent harmonics on the air gap flux. Permanent magnet synchronous machines can be realized with either embedded or surface magnets on the rotor, and the location of the magnets can have a significant effect on the motor’s mechanical and electrical characteristics, especially on the inductances of the machine. As the relative permeability of the modern rare-earth magnets, such as the NdFeB is only slightly above unity, the effective air gap becomes long with a surface magnet construction. This makes the direct-axis inductance very low, which has a substantial effect on the machine’s overloading capability, and also on the field weakening characteristics. As the pull-out torque is inversely proportional to the d-axis inductance, the pull-out torque becomes very high. Typically, the per-unit values of the d-axis synchronous inductances of the SMPMSM servos vary between 0.2–0.35 p.u., and consequently the pull-out torque is in the range of 4–6 p.u., which makes them well suitable in motion control applications. The drawback of a low Ld –value is the very short field weakening range, as the armature reaction with a surface magnet construction is very weak. This means that a high demagnetizing stator current component would be required to decrease the air gap flux, and consequently, there would be very little current left on the q-axis to produce the torque. Direct-axis inductance of a machine having embedded magnets becomes high, as the rotor magnets per pole form a parallel connection for the flux, while with a surface magnet construction they are connected in series. With equivalent magnets, the rotor reluctance of the surface-magnet construction is therefore double compared to an embedded-magnet construction, and the inductance is inversely proportional to the reluctance. With embedded-magnets, the direct-axis inductance is further increased because of the higher rotor leakage flux. Three basic configurations of PMSMs are shown in Fig. 3.3.



(a) (b) (c)

Figure 3.3 Three basic configurations of PMSMs

The most common PM rotor constructions are

a) Non-salient surface magnet rotor, due to high d axis reluctance, L_d is low and consequently the pull-out torque high.

b) Salient pole surface magnet rotor with inset magnets, which is basically the same as a), but this type produces also some reluctance torque.

c) Embedded magnets in the rotor, which has a high L_d value, and consequently a poor overloading capability, but a lot better field weakening characteristics than with the surface magnet constructions.

Typically the construction of the PMSM servomotor is somewhere between (a) and (b), and the q-axis inductance is larger. Industrial PMSMs often represent the type (c).

In addition to the good overloading capability, another reason that makes the surface magnet construction favorable in servo applications is the lower inertia. With multi-pole machines, the rotor and the stator yokes can be made very thin, and all the additional iron can be removed from the rotor to provide a lower inertia. These large holes also improve the heat transfer from the rotor, as the high frequency flux pulsations generate heat on the magnets and on the rotor iron. As the servomotors must typically rotate very fast, gluing does usually not suffice in attaching the magnets on the surface of the rotor, and some non-magnetic material, such as a stainless steel cylinder or a fiber-glass band must be used to support the magnets. The problem in using steel is that it is a highly conductive material, and the air gap harmonics strongly generate losses and consequently heat in it. Therefore, a fiber-glass band or a plastic cylinder is more often used for the magnet retaining. Unfortunately, electrical insulators are also thermal insulators, which mean that their thermal conductivity for the heat generated in the rotor iron and in the magnets is poor. The temperature rise of the magnets decreases their remanence flux density, and consequently the torque production.

The rotor in Fig. 3.3 (b) with inset surface magnets has better mechanical characteristics, but on the other hand, it has higher leakages between two adjacent magnets. In addition to the higher leakage, the torque production decreases more as the motor must operate at higher pole angle due to increased q-axis inductance compared to a non-salient rotor. Typically, the construction of commercial servomotors is somewhere between (a) and (b) in Fig. 3.3, that is, the magnets are slightly embedded in the rotor. This improves the mechanical strength of the rotor and introduces a reluctance difference-based term in the torque. According to measurements made at LUT for eight different commercial servomotors in the power range of 3–5 kW, the values for the q-axis inductances were 10–20 % higher than the values in the d-direction.

With buried magnets and flux concentration, a sinusoidal air gap flux density distribution is possible with simple rectangular magnets. A sinusoidal air gap flux distribution significantly decreases the cogging torque especially with low-speed multi-pole machines that have a low number of slots per poles per phase number q. Also, it is possible to increase the air gap flux density beyond the remanence flux density of the magnets with a flux concentration arrangement, and the machine can produce more torque at a given volume. This is especially desirable in low speed applications, such as in wind generators and in propulsion motors where the space is limited. As the direct-axis inductance is typically high with a buried magnet construction, the overloading capability will be poor, which makes this motor type incompetent in motion control applications. Typically, the embedded v-shape magnet machine can have L_d approx. 0.7 p.u, which means only 1.4 p.u. overloading capability according to the load-angle equation of a synchronous machine with the assumption that EPM = us = 1 p.u. and $L_d = L_q$. If there is a reluctance difference in the machine, the maximum torque can be somewhat larger. It must, however, be borne in mind that despite the embedded magnets, it is of course possible to increase the physical air gap large enough, and thereby to decrease the direct axis inductance of the machine remarkably from the value given above. However, the consumption of the magnet material is increased remarkably in such a case.

3.4 ROTOR CONFIGURATIONS

3.4.1 MERRILL’S ROTOR

The first successful construction of a PM rotor for small synchronous motors rated at high frequencies was patented by F.W. Merrill (Perera). It was a four-pole motor similar to the two-pole motor shown in Fig. 3.4a. The laminated external ring has deep narrow slots between each of the PM poles (Fig. 3.4a). The leakage flux produced by the PM can be adjusted by changing the width of the narrow slots. The Alnico PM is protected against demagnetization because the armature flux at starting and reversal goes through the laminated rings and narrow slots omitting the PM. The PM is mounted on the shaft with the aid of an aluminum or zinc alloy sleeve. The thickness of the laminated rotor ring is chosen such that its magnetic flux density is approximately 1.5 T when the rotor and stator are assembled. Magnetic flux density in the rotor teeth can be up to 2 T.

3.4.2 INTERIOR-TYPE PM MOTORS

The interior-magnet rotor has radially magnetized and alternately poled magnets (Fig. 3.4b). Because the magnet pole area is smaller than the pole area at the rotor surface, the air gap flux density on open circuit is less than the flux density in the magnet (Merrill). The synchronous reactance in d-axis is smaller than that in q-axis since the q-axis magnetic flux can pass through the steel pole pieces without crossing the PMs. The magnet is very well protected against centrifugal forces. Such a design is recommended for high frequency high speed motors.

3.4.3 SURFACE PM MOTORS

The surface magnet motor can have magnets magnetized radially (Fig. 3.4c) or sometimes circumferentially. An external high conductivity non ferromagnetic cylinder is sometimes used. It protects the PMs against the demagnetizing action of armature reaction and centrifugal forces, provides an asynchronous starting torque, and acts as a damper. If rare-earth PMs are used, the synchronous reactance in the d- and q-axis are practically the same.

3.4.4 INSET-TYPE PM ROTOR

In the inset-type motors (Fig. 3.4d) PMs are magnetized radially and embedded in shallow slots. The rotor magnetic circuit can be laminated or made of solid steel. In the first case a starting cage winding or external non ferromagnetic cylinder is required. The q-axis synchronous reactance is greater than that in the d-axis. In general, the EMF E_f induced by the PMs is lower than that in surface PM rotors.

3.4.5 BURIED PM MOTORS

The buried-magnet, rotor has circumferentially magnetized PMs embedded in deep slots (Fig. 3.4e). Because of circumferential magnetization, the height h_M of the PM is in tangential direction, i.e., along the pole pitch. The effective pole arc coefficient α_i is dependent on the slot width. The synchronous reactance in q-axis is greater than that in d-axis. A starting asynchronous torque is produced with the aid of both a cage winding incorporated in slots in the rotor pole shoes (laminated core) and solid salient pole shoes made of mild steel. The width of the iron bridge between the inner ends of the neighboring magnets has to be carefully chosen. The application of a non ferromagnetic shaft is essential (Fig. 5.10). With a ferromagnetic shaft, a large portion of useless magnetic flux goes through the shaft (Binns) (Fig. 3.5a). A buried-magnet rotor should be equipped with a non ferromagnetic shaft (Fig. 3.5b) or a non ferromagnetic sleeve between the ferromagnetic shaft and rotor core should be used.

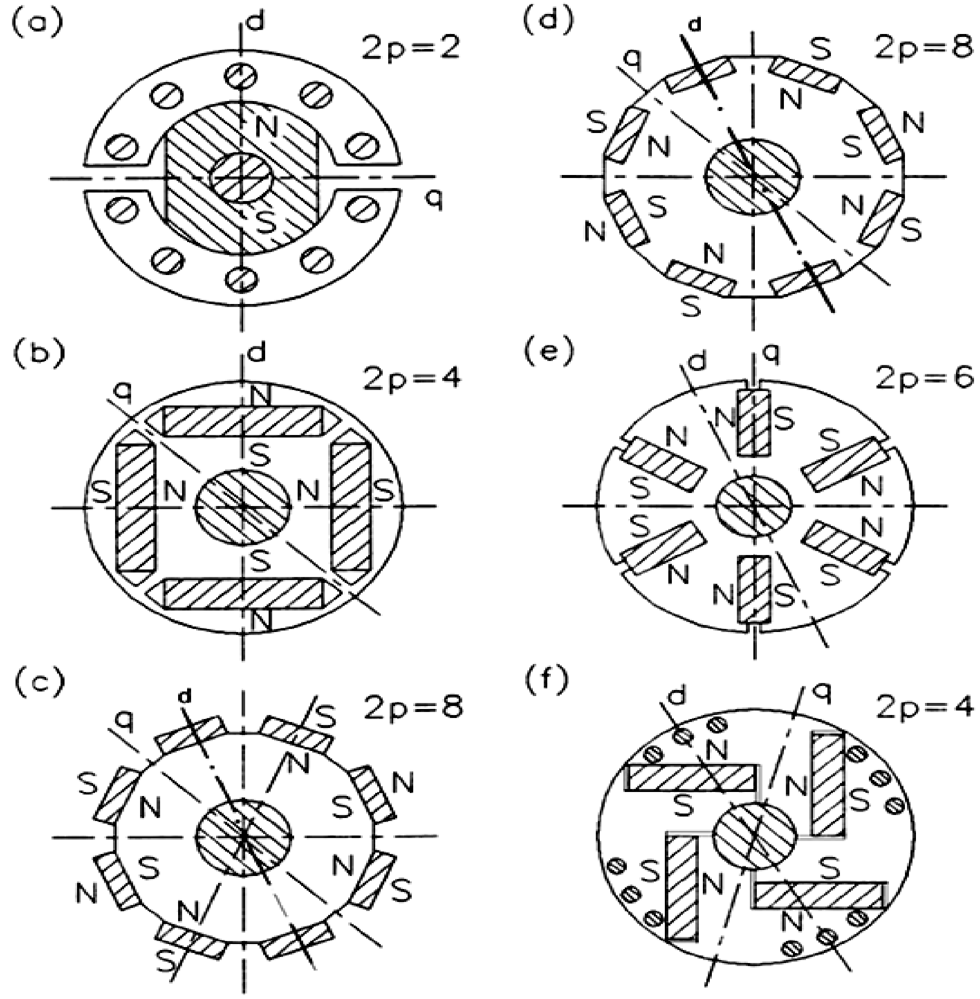
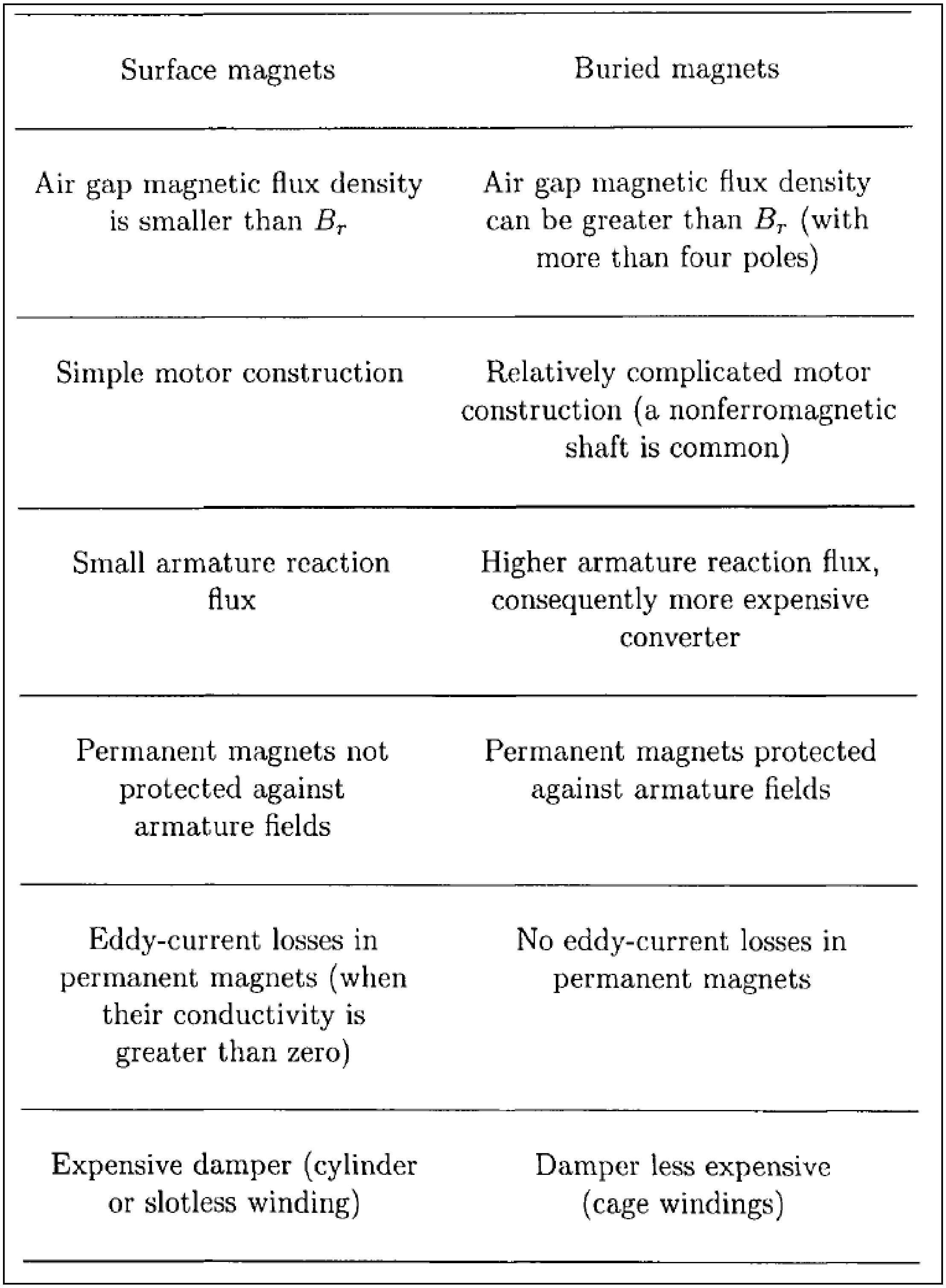


Figure 3.4: Rotor configurations for PM synchronous motors: (a) classical configuration, (b) interior-magnet rotor, (c) surface-magnet rotor, (d) inset magnet rotor, (e) rotor with buried magnets symmetrically distributed, (f) rotor with buried magnets asymmetrically distributed.

A brief comparison between surface and buried magnet synchronous motors is given in Table 3.1

Table 3.1: Comparison between PM synchronous motors with surface and buried magnets.



Surface magnets	Buried magnets
Air gap magnetic flux density is smaller than B_r	Air gap magnetic flux density can be greater than B_r (with more than four poles)
Simple motor construction	Relatively complicated motor construction (a nonferromagnetic shaft is common)
Small armature reaction flux	Higher armature reaction flux, consequently more expensive converter
Permanent magnets not protected against armature fields	Permanent magnets protected against armature fields
Eddy-current losses in permanent magnets (when their conductivity is greater than zero)	No eddy-current losses in permanent magnets
Expensive damper (cylinder or slotless winding)	Damper less expensive (cage windings)

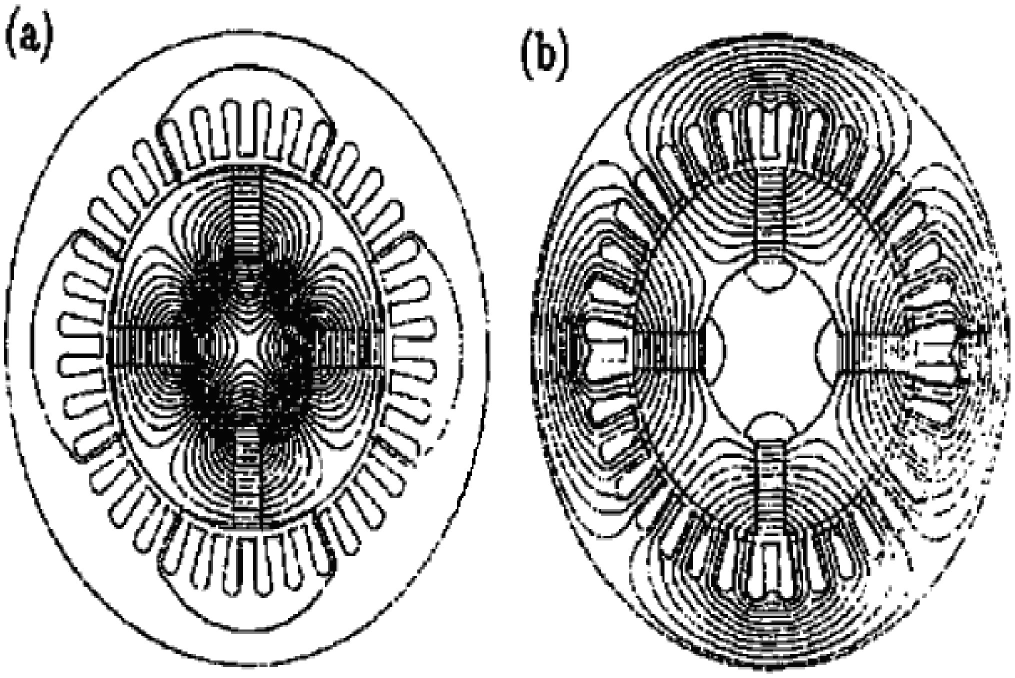


Figure 3.5: Magnetic flux distribution in the cross section of a buried magnet synchronous motor: (a) improperly designed rotor with ferromagnetic shaft, (b) rotor with non ferromagnetic shaft.

An alternative construction is a rotor with asymmetrically distributed buried magnets (Fig. 3.4e) developed by Siemens AG (Siemens).

3.5 PRINCIPLE OF OPERATION OF PMSM

The PMSM rotate because of the magnetic attraction between the rotor and the stator poles. When the rotor poles are facing stator poles of the opposite polarity, a strong magnetic attraction is set up between them. The mutual attraction locks the rotor and the stator poles together and the rotor is literally yanked into step with the revolving stator magnetic field. At no-load conditions, rotor poles are directly opposite to the stator poles and their axes coincide. At load conditions the rotor poles lag behind the stator poles, but the rotor continues to turn at synchronous speed, the mechanical angle “θ” between the poles increases progressively as we increase the load.

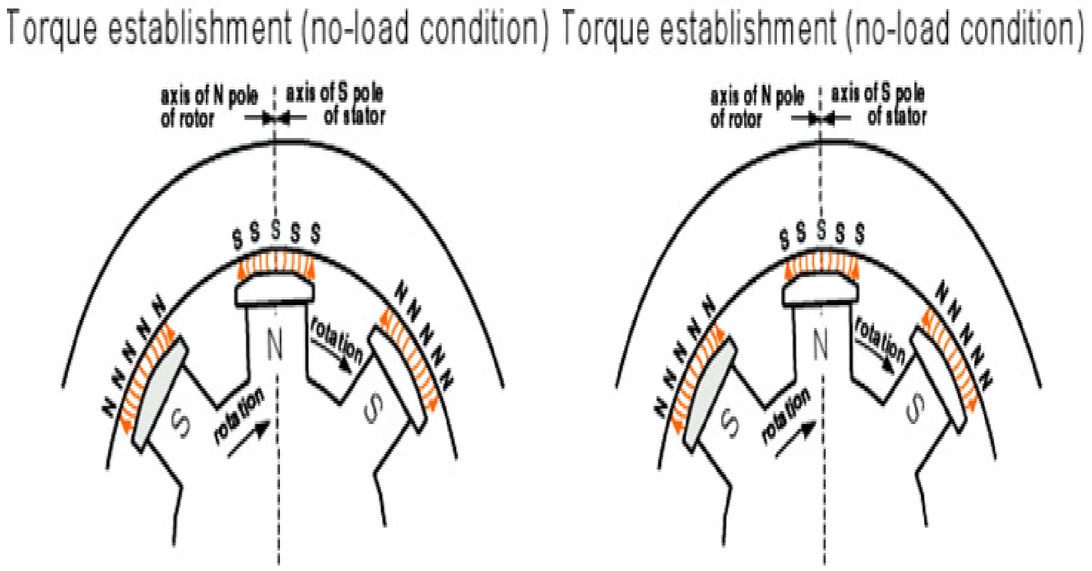
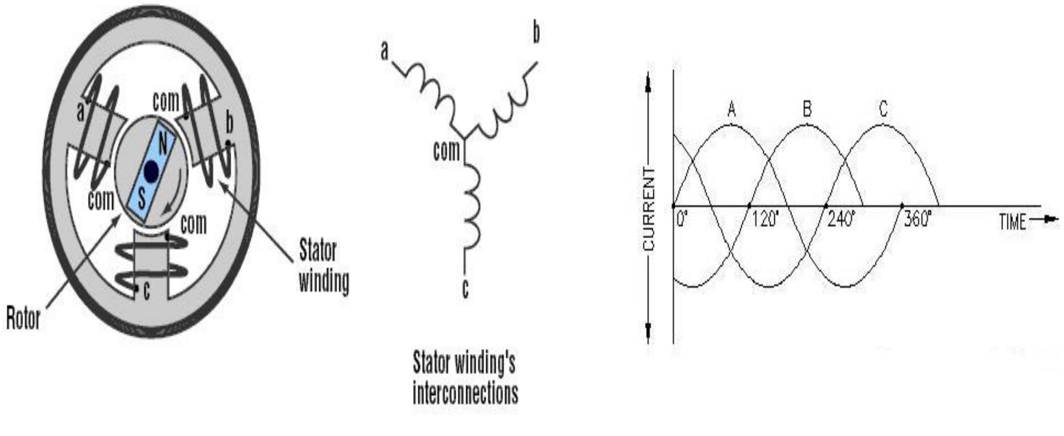


Figure 3.6: Torque Establishment

- Permanent magnet rotor (a)
- Three-phase Y-connected stator (b)
- Sinusoidal phase currents (c)
- Each phase is 120º displaced from the others
- Phase currents must sum to 0



(a) (b) (c)

Figure 3.7: Rotor, Stator, Phase Currents

3.6 STARTING

3.6.1 ASYNCHRONOUS STARTING

A synchronous motor which has a cage winding on its rotor can be started as a cage induction motor. The starting torque is produced as a result of the interaction between the stator rotating magnetic field and the rotor winding currents. In synchronous motors with solid salient poles, the cage winding is not necessary since the eddy currents induced in solid pole shoes can interact with the stator magnetic field.

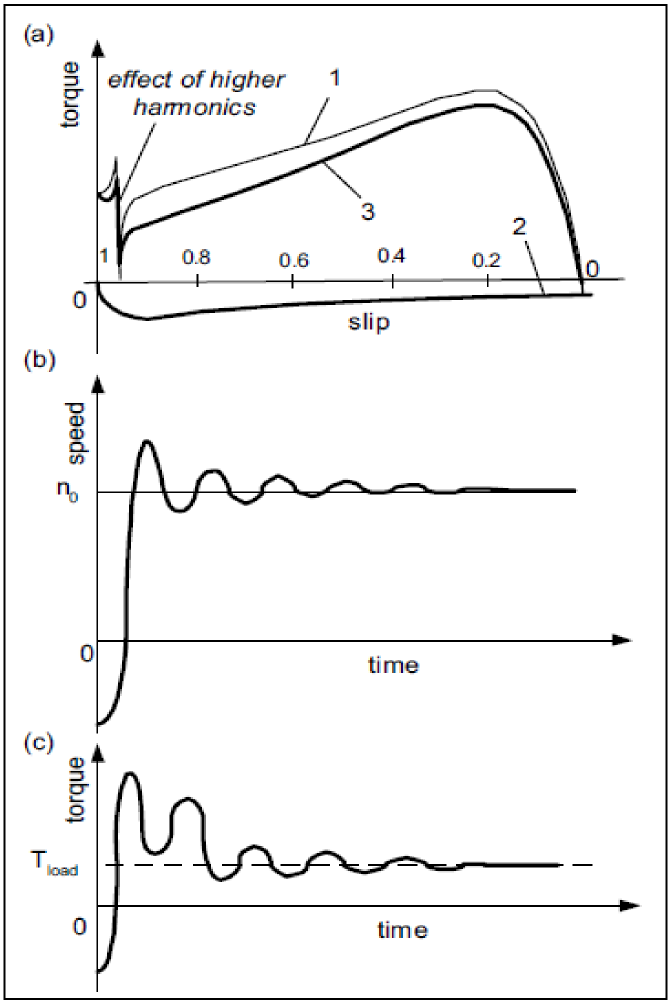


Figure 3.8: Characteristics of a line start PM brushless motor: (a) steady-state torque slip characteristic; (b) speed–time characteristic; (c) torque–time characteristic. 1 — asynchronous torque, 2 — braking torque produced by PMs, 3 — resultant torque, n_0 — steady-state speed, T_{load} — load torque.

3.6.2 FREQUENCY-CHANGE STARTING

The frequency of the voltage applied to the motor is smoothly changed from the value close to zero to the rated value. The motor runs synchronously during the entire starting period. Variable voltage variable frequency (VVVF) solid state inverters are commonly used.

3.6.3 STARTING BY MEANS OF AN AUXILIARY MOTOR

A synchronous motor is not self-starting. Auxiliary induction motors are frequently used for starting large synchronous motors with electromagnetic excitation. The synchronous motor has an auxiliary starting motor on its shaft, capable of bringing it up to the synchronous speed at which time synchronizing with the power circuit is possible. The unexcited synchronous motor is accelerated to almost synchronous speed using a smaller induction motor. When the speed is close to the synchronous speed first the armature voltage and then the excitation voltage is switched on, and the synchronous motor is pulled into synchronism.

The disadvantage of this method is it’s impossible to start the motor under load. It would be impractical to use an auxiliary motor of the same rating as that of the synchronous motor and expensive installation.

3.7 SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

3.7.1 SCALAR CONTROL

The principle of the scalar control is to maintain a constant V/Hz ratio almost through the whole speed range operation since only the magnitude and frequency of the supply voltages is controlled. The V/Hz ratio is calculated from the nominal values (voltage and frequency) of the PMSM. By maintaining a constant V/Hz ratio the stator flux of the PMSM can be maintained relatively constant in steady state. If the V/Hz ratio increases then the PMSM becomes overexcited and if it decreases then it becomes under excited (Stulrajter). At very low speeds it is necessary to compensate for the stator resistance voltage drop so a V/Hz ratio higher than the nominal one is needed. The scalar control is the most common control strategy used for IM drives.

The PMSM scalar control is a good alternative in applications where good dynamic performance is not required (fans, pumps, blowers). Scalar control is performed without the need of a position encoder and the speed of the rotor can be estimated by looking at the frequency of the supply voltage (Stulrajter). When using scalar control there is no need for high capability DSP as in the case of vector control.

Some PMSMs have so called build in damper windings which help to stabilize the PMSM especially when scalar controlled. The damper windings basically are similar to the squirrel cage rotor of an IM. In a PMSM the damper windings produce some amount of asynchronous torque similarly as in an IM when needed thus helping the PMSM to synchronize. When the PMSM is synchronized then there is no current induced in the damper windings since the slip is zero and then there is no asynchronous torque produced.

In a scalar controlled PMSM the stator currents are not controlled directly. A scalar controlled PMSM can become unstable easily especially when the load torque reaches the break down torque value. Considering its disadvantages the scalar control is not suitable for low speed control of PMSM in high dynamic applications.

Scalar control is based on relationships valid in steady state. It is simple but due to the inherent coupling effect (i.e., torque and flux are proportional to the voltage or current and frequency) gives sluggish response and the system can be easily prone to instability. In this only magnitude and frequency of voltage, current, etc are controlled. Scalar control is used where several motors are driven in parallel by the same inverter. In order to overcome these problems we are going for vector control.

3.7.2 VECTOR CONTROL

Vector control offers superior performance when compared to scalar control. Vector control eliminates almost all the disadvantages of scalar control. The main idea of vector control is to control not only the magnitude and frequency of the supply voltages but also the angle.

With other words said the magnitude and angles of the space vectors is controlled. There are different kind of vector controls, the two most commonly used being DTC and FOC.

3.7.2.1 DIRECT TORQUE CONTROL

Direct torque control was introduced on the market by ABB. The DTC has some advantages like simple control scheme, good dynamic response and it does not needs rotor speed or position feedback thus being considered a sensor less control technique.

The control scheme of classical DTC is much simpler than that of FOC as there is no reference frame transformation or position and speed measurement needed. The DTC scheme consists of torque and stator flux estimators, torque and flux hysteresis comparators a switching table and a voltage source inverter. The principle of DTC is to choose a voltage vector to control both stator flux and torque simultaneously. The stator currents and DC-link voltage are sampled and used in the flux and torque estimation. The estimated torque and flux magnitudes are compared with their reference values in the hysteresis comparators and then the outputs of the hysteresis comparators are feed to the switching table in order to select the appropriate voltage vectors in each sampling period (Paturca).

The drawbacks of classical DTC are high torque and current ripples during steady state operation unless operated at very high switching frequencies (40 KHz) which increases the overall cost of the drive system.

3.7.2.2 FIELD ORIENTED CONTROL

The objective of field oriented control is to be able to control the PMSM as a separately excited DC machine meaning that the flux and torque can be controlled separately (in a decoupled way). The instantaneous stator currents are transformed to the dq rotating reference frame by means using mathematical equations and taking into account the rotor position. The flux is controlled through the d - axis current while the torque is controlled through the q - axis current. It is not enough to use only the dq transformation in order to achieve decoupled control of flux and torque since there is coupling between the two axes which may be canceled out by subtracting from the dq - axis reference voltages the appropriate coupling terms. Two types of field oriented control are possible for the PMSM: rotor oriented FOC and stator oriented FOC.

Due to its advantages like low torque and current ripple, constant VSI switching frequency, low audible noise FOC control scheme was chosen for further analysis.

The field-oriented control technique brought on a renaissance in modern high performance control of ac drives. This control method has found wide acceptance in applications such as paper mills, textile mills, steel rolling mills, machine tools, servos, and robotics. With vector or decoupling control, the dynamics of ac drives is similar to that of dc drives, and with current control, the conventional stability limit of ac machine does not arise.

This is indeed a remarkable accomplishment. The direct or feedback method, which was developed by Blaschke, depends on unit vector generation from the machine terminal voltages. As usual, harmonic noise becomes a problem in feedback signal processing, and the method is difficult to use near zero speed because of the dominance of stator drop. Of course, for servo-type applications, the unit vectors can be computed from stator currents and speed signals. In the indirect or feed forward method, which was developed by Hasse, the above problems do not exist, but the controller is highly dependent on machine parameters.

This method has gained popularity in industrial applications. Recently, a hybrid or universal vector control method has been suggested, where the indirect vector control operates in the lower speed range and is switched to parameter-independent direct vector control in the higher speed range. It should be mentioned here that, the vector control can be applied to both induction and synchronous machines and, in fact can be applied to the general AC system for independent active and reactive power control.

By using the Vector control, the performance of the ac machine can be made similar to that of a separately excited DC motor by the orientation of the stator MMF or current vector in relation to the rotor flux to achieve a desired objective.

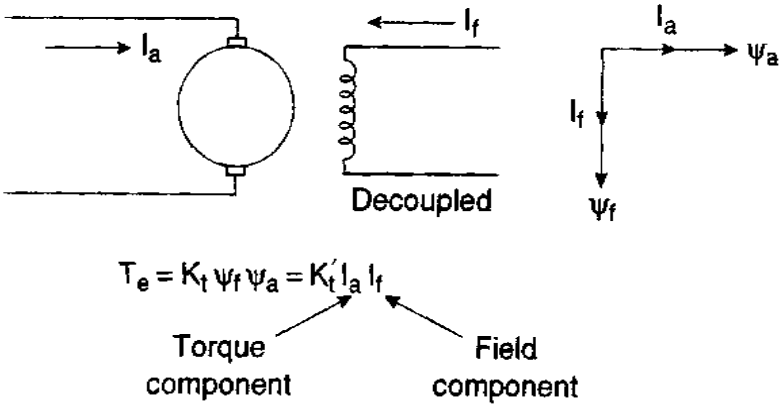


Figure 3.9: Separately Excited Dc Motor

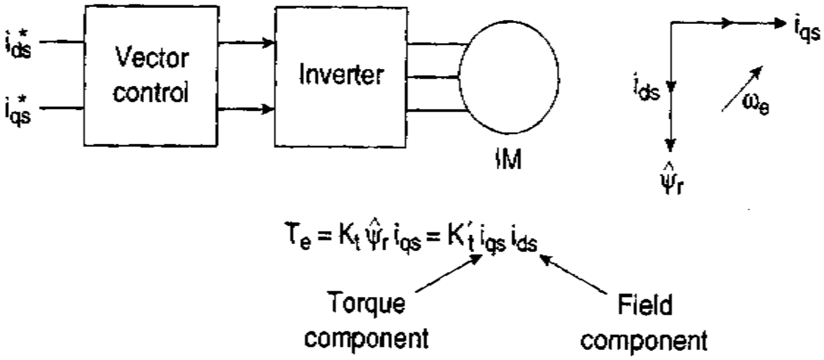


Figure 3.10: Vector Controlled Ac Motor

In vector control we are making the i_a and i_f which are responsible for producing the fluxes of Ψ_a and Ψ_f orthogonal to each other.

In case of DC machine, the construction is such that i_a and i_f are perpendicular to each other. I_a is responsible for torque and if is responsible for the production of flux. When torque is controlled by i_a the Ψ_f is not affected. When flux is controlled by if, there will be no effect on Ψ_a. Therefore a DC motor has fast transient response.

But due to the inherent coupling effect the ac machine cannot give such fast response. In order to exhibit the DC machine characteristics, the machine is controlled in the synchronously rotating reference frame (d^e-q^e), where the sinusoidal machine variables appear as DC quantities in the steady state.

The performance of vector control is comparable to DC machine. It produces less ripples but the system is more complex and less robust when compared to DTC control.

3.8 FOC CONTROL PROPERTIES

There are several control properties that may be used for a PMSM. The most common control properties are discussed.

3.8.1 UNITY POWER FACTOR STRATEGY

The goal of this control property is to control the dq - axis currents in such a way that the instantaneous stator currents will be in phase with the instantaneous stator voltages thus obtaining unity power factor. Since the power factor cos (ψ) = 1 the reactive power is zero.

That means that the input power to the PMSM is only active power thus the V A rating of the VSI is minimized (Perera).

3.8.2 CONSTANT STATOR FLUX STRATEGY

In this control property the magnitude of the stator flux is limited thus limiting the stator voltage requirement. When the stator flux is limited then also the torque producing capability of the PMSM is also limited. Usually in the case of the stator flux control for PMSM the magnitude of the stator flux is maintained constant and equal to the permanent magnet flux linkage. This way the stator voltage requirement of the PMSM is kept low and the torque producing capability of the machine is not degraded (Perera).

3.8.3 MAXIMUM TORQUE PER AMPERE STRATEGY

By using this control property the torque producing capability of the machine is maximized since the minimum stator current magnitude can be applied to the machine for a required electromagnetic torque. This way the copper losses are minimized. If the core losses are negligible then the maximum efficiency of the PMSM can be also obtained by using this control property. In the case of SMPMSM the maximum torque per ampere control property is the same with the constant torque angle property since there is almost no difference in the dq - axis inductances thus the reluctance torque is almost inexistent (Perera).

3.8.4 CONSTANT TORQUE ANGLE STRATEGY

The constant torque angle control property is one of the easiest to implement since the d - axis reference current is set to zero. It is also called $i^r_{ds} = 0$ control property or $\alpha = \frac{\pi}{2}$ control property. The idea of this control property is to maintain a constant angle of 90deg electrical between the current space vector and permanent magnet flux axis. This way all the current is projected on the q - axis. By using this control strategy for an IPMSM the reluctance component of the torque is lost. This control property is a good choice in the case of a SMPMSM since the reluctance torque is almost inexistent (Perera).

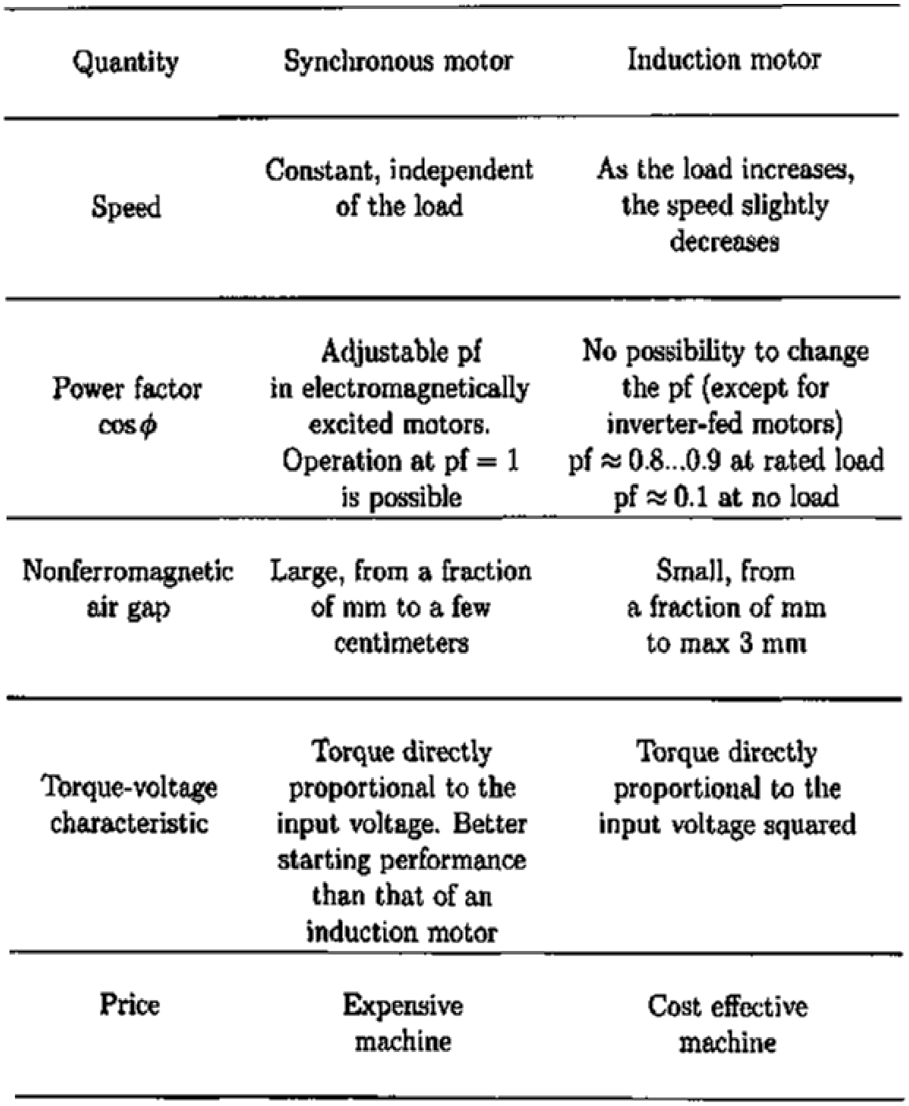
In this project the V A rating of the inverter is not an issue since the machine needs to be sensorlessly controlled at low speed. The stator voltage requirement is also not an issue since the machine is operated at low speed thus the required voltage is not high. Since the machine used in this project is a SMPMSM and it needs to be energy optimally controlled a good choice is the constant torque angle (maximum torque per ampere) control property which is also the maximum efficiency control property if the core losses are negligible.

3.9 COMPARISON BETWEEN SYNCHRONOUS AND INDUCTION MOTORS

PM synchronous motors, as compared with their induction counter parts, do not have rotor winding losses and require simple line commutated inverters which are more efficient than forced commutated inverters. Table 3.2 contains a comparison of the speed, power factor cos ϕ, air gap, torque voltage characteristics, and price of synchronous and induction motors. A larger air gap in synchronous motors makes them more reliable than induction motors. The increased air gap is required to minimize the effect of the armature reaction, to reduce the synchronous reactance (if necessary) and to improve the stability.

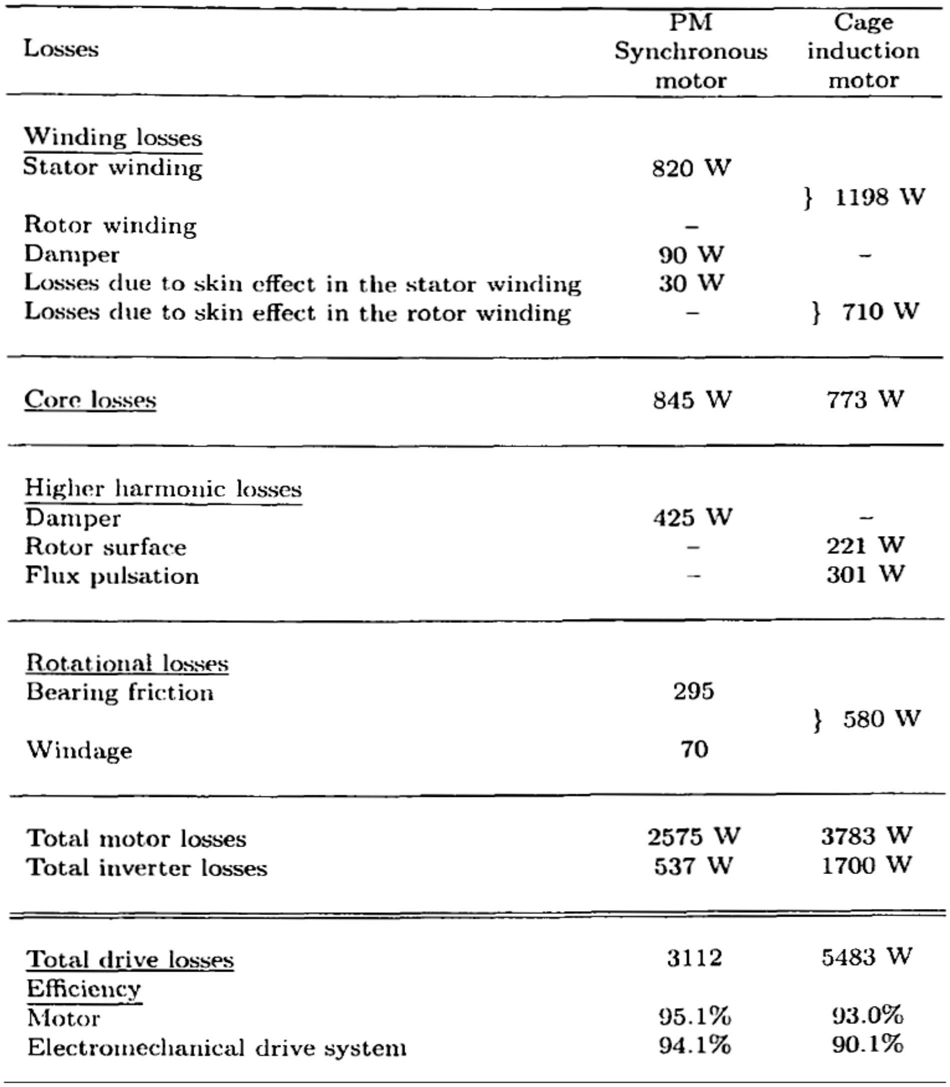
Table 3.3 compares 50-kW, 6000-rpm, 200-Hz PM synchronous and cage induction motor drives (Andresen). The total power losses of the PM synchronous motor drive are reduced by 43% as compared with the induction motor drive. Thus the efficiency has been increased from 90.1 to 94.1% by 4% (2 kW power saving) (Andresen).

Table 3.2: Comparison between PM synchronous and induction motors.



Quantity	Synchronous motor	Induction motor
Speed	Constant, independent of the load	As the load increases, the speed slightly decreases
Power factor $\cos\phi$	Adjustable pf in electromagnetically excited motors. Operation at pf = 1 is possible	No possibility to change the pf (except for inverter-fed motors) pf ≈ 0.8...0.9 at rated load pf ≈ 0.1 at no load
Nonferromagnetic air gap	Large, from a fraction of mm to a few centimeters	Small, from a fraction of mm to max 3 mm
Torque-voltage characteristic	Torque directly proportional to the input voltage. Better starting performance than that of an induction motor	Torque directly proportional to the input voltage squared
Price	Expensive machine	Cost effective machine

Table 3.3: Power losses and efficiency of PM synchronous and cage induction motor drives rated at 50 kW, 6O00 rpm and 200 Hz.



Losses	PM Synchronous motor	Cage induction motor
Winding losses		
Stator winding	820 W	} 1198 W
Rotor winding	–	
Damper	90 W	–
Losses due to skin effect in the stator winding	30 W	} 710 W
Losses due to skin effect in the rotor winding	–	
Core losses	845 W	773 W
Higher harmonic losses		
Damper	425 W	–
Rotor surface	–	221 W
Flux pulsation	–	301 W
Rotational losses		
Bearing friction	295	} 580 W
Windage	70	
Total motor losses	2575 W	3783 W
Total inverter losses	537 W	1700 W
Total drive losses	3112	5483 W
Efficiency		
Motor	95.1%	93.0%
Electromechanical drive system	94.1%	90.1%

3.10 CLOUSER

Thus, this chapter describes about theoretical review of permanent magnet motors drives which includes permanent magnet materials, classification of permanent magnet motors, and construction detail of PM motors, different types of rotor configurations, and principle of operation and starting of PM motors and speed control methods which includes the control properties of FOC.

CHAPTER 4

DESCRIPTION OF THE DRIVE SYSTEM

4.1 INTRODUCTION

This chapter deals with the description of the different components of the drive system such as permanent magnet motors, position sensors, inverters and current controllers of the drive system. A review of permanent magnet materials and classification of permanent magnet motors is also given.

4.2 PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE SYSTEM

The motor drive consists of four main components, the PM motor, inverter, control unit and the position sensor. The components are connected as shown in Figure 4.1.

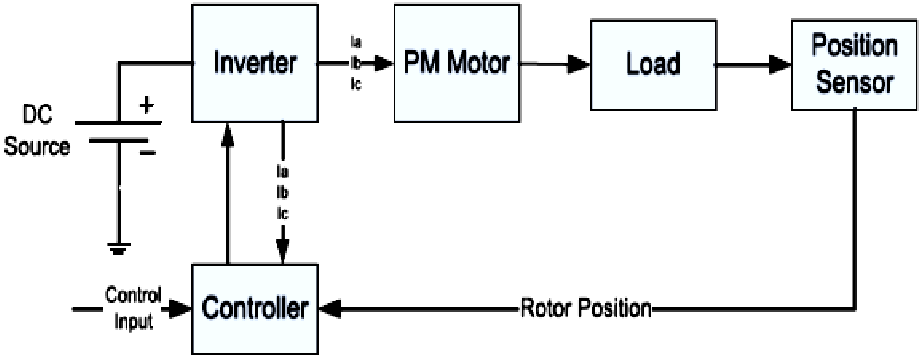


Figure 4.1 Drive System Schematic

PM Motor: It is a motor that uses permanent magnets to produce the air gap magnetic field. The most commonly used magnetic materials are rare earth magnets such as NdFeB, SmCo, Strontium Ferrite or Barium ferrite etc.

Inverter: The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage.

Position sensor: Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor. These are mainly used for determining the position of the rotor. The most commonly used position sensors are encoders and resolvers. Depending on the application and performance desired by the motor a position sensor with the required accuracy can be selected.

Control unit: The control input and the rotor position signal is given to the controller and depending upon both the signals it will generate the output which is given to the inverter.

4.3 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.

Figure 4.2: Permanent Magnet Synchronous Motor

The use of permanent magnets (PMs) in construction of electrical machines brings the benefits of no electrical energy is absorbed by the field excitation system and thus there are no excitation losses which means substantial increase in the efficiency, higher torque and/or output power per volume than when using electromagnetic excitation, better dynamic performance than motors with electromagnetic excitation (higher magnetic flux density in the air gap), simplification of construction and maintenance**,** reduction of prices for some types of machines**.**

4.3.1 PERMANENT MAGNET MATERIALS

The properties of the permanent magnet material will 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 4.3.

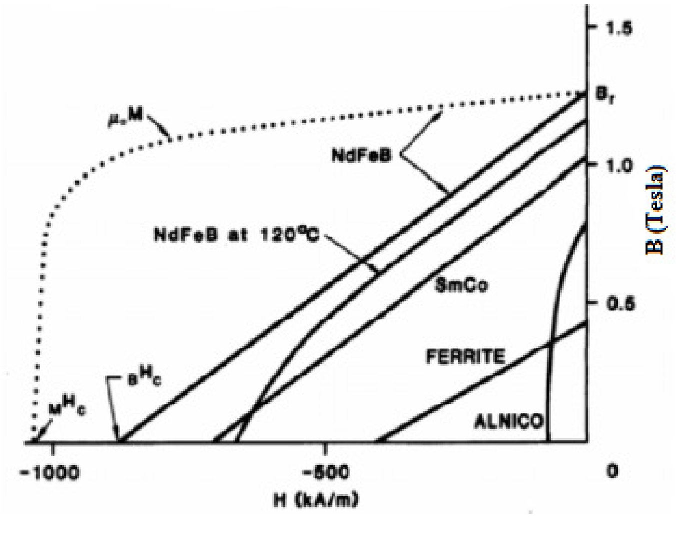


Figure 4.3: Flux Density Vs Magnetizing Field of Permanent Magnetic Materials

4.3.2 CLASSIFICATION OF PERMANENT MAGNET MOTORS

The permanent magnet synchronous motors are broadly classified according to the direction of field flux density distribution and permanent magnet radial field motors as follows.

4.3.2.1 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.

4.3.2.2 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.

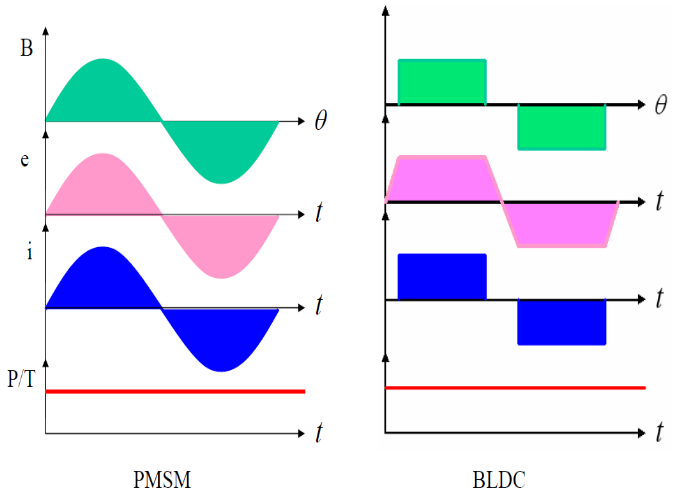


Figure 4.4: waveforms of PMSM and BLDC machines

4.3.2.3 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 .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 $L_d = L_q$.

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 4.5 shows the placement of the magnet.

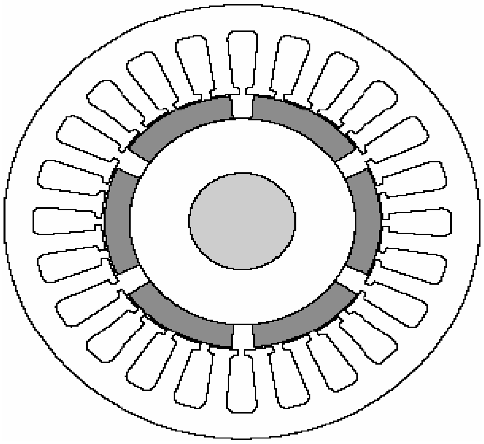


Figure 4.5: Surface Permanent Magnet Motor

Interior PM Motors have interior mounted permanent magnet rotor as shown in Figure 4.6. 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 ($L_q > L_d$).

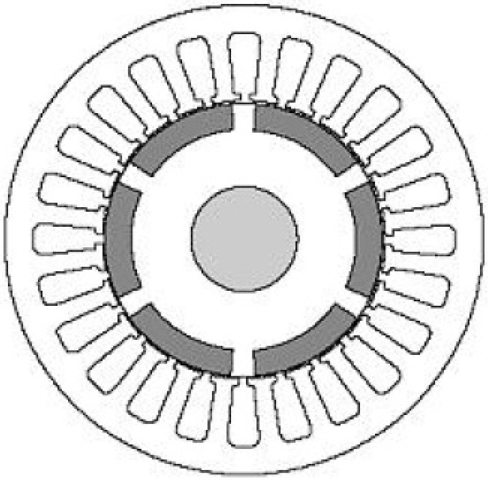


Figure 4.6: Interior Permanent Magnet Motor

4.4 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.

4.4.1 OPTICAL ENCODERS

The most popular type of encoder is the optical encoder as shown in Figure 4.7, which consists of a rotating disk, a light source, and a photo detector (light sensor). The disk, is mounted on the rotating shaft, has coded patterns of opaque and transparent sectors. As the disk rotates, these patterns interrupt the light emitted onto the photo detector, generating a digital pulse or output signal.

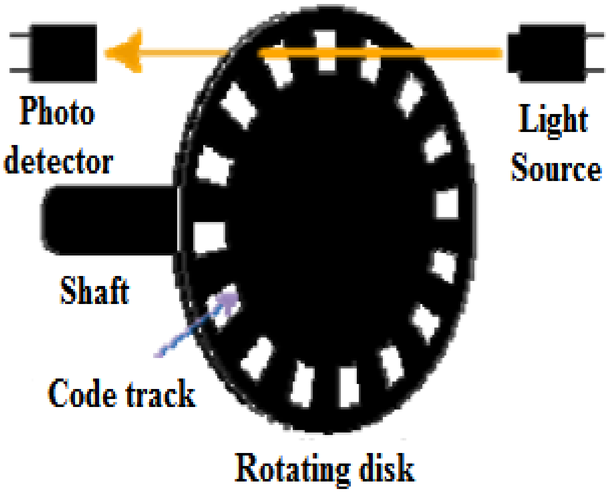


Figure 4.7: Optical Encoder

Optical encoders offer the advantages of digital interface. There are two types of optical encoder's Incremental encoder and absolute encoder.

4.4.1.1 INCREMENTAL ENCODERS

Incremental encoders have good precision and are simple to implement but they suffer from lack of information when the motor is at rest position and in order for precise position the motor most be stop at the starting point.

The most common type of incremental encoder uses two output channels (A and B) to sense position. Using two code tracks with sectors positioned 90° degrees out of phase, the two output channels of the quadrature encoder indicate both position and direction of rotation as shown in Figure 4.8. If A leads B, for example, the disk is rotating in a clockwise direction. If B leads A, then the disk is rotating in a counter-clockwise direction. By monitoring both, the number of pulses and the relative phase of signals A and B, it's possible to track position and direction of rotation. Some quadrature encoders also include a third output channel, called a zero or index or reference signal, which supplies a single pulse per revolution. This single pulse is used for precise determination of a reference position. The precision of the encoder is fix by its code disk but it can be increased by detecting the Up and Down transitions on both the A and B channels.

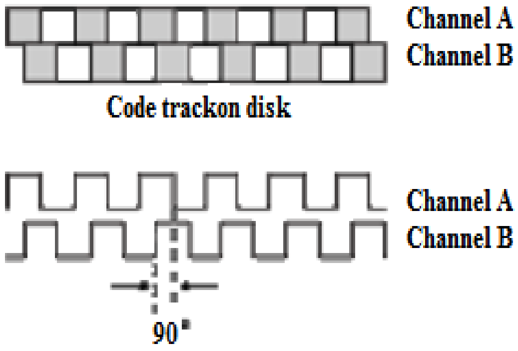


Figure 4.8: Quadrature Encoder Channels

4.4.1.2 ABSOLUTE ENCODERS

The absolute encoder, as shown in Figure 4.9 captures the exact position of the rotor with a precision directly related to the number of bits of the encoder. It can rotate indefinitely and even if the motor stops the position can be measured or obtained.

It provides a “whole word” output with a unique code pattern representing each position. This code is derived from independent tracks on the encoder disc (one for each “bit” of resolution) corresponding to individual photo detectors. The output from these detectors is HI (light) or LO (dark) depending on the code disc pattern for that particular position.

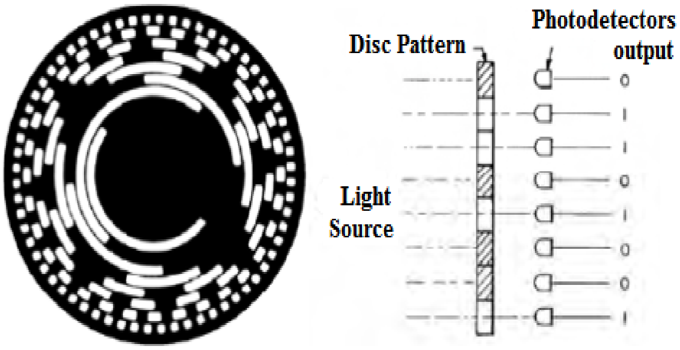


Figure 4.9: Absolute Encoder

Absolute encoders are used in applications where a device is inactive for long periods of time or moves at a slow rate, such as flood gate control, telescopes, cranes, valves, etc. They are also recommended in systems that must retain position information through a power outage.

4.5 POSITION REVOLVER

Position revolver as shown in Figure 4.10, also called rotary transformers works on the transformer principle. The primary winding is placed on the rotor and depending upon the rotor shaft angle the induced voltage at the two secondary windings of the transformer shifted by 90° would be different. The position can be calculated using the two voltages.

The resolver is basically a rotary transformer with one rotating reference winding (V_{ref}) and two stator windings. The reference winding is fixed on the rotor, and therefore, it rotates jointly with the shaft passing the output windings, as is depicted in Figure 4.9. Two stator windings are placed in quadrature (shifted by 90°) with one another and generate the sine and cosine voltages (V_{sin}, V_{cos}) respectively. Both windings will be further referred to as output windings. In consequence of the excitement applied on the reference winding V_{ref} and along with the angular movement of the motor shaft θ, the respective voltages are generated by resolver output windings $V_{sin,}$ V_{cos}.

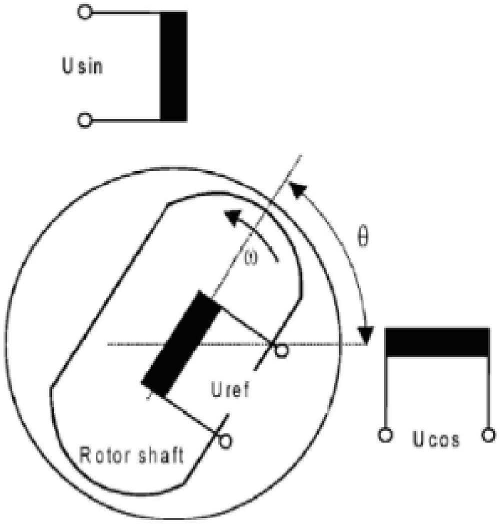


Figure 4.10: Resolver

The frequency of the generated voltages is identical to the reference voltage and their amplitudes vary according to the sine and cosine of the shaft angle θ. Considering that one of the output windings is aligned with the reference winding, then it is generated full voltage on that output winding and zero voltage on the other output winding and vice versa. The rotor angle θ can be extracted from these voltages shown in Figure 4.10.

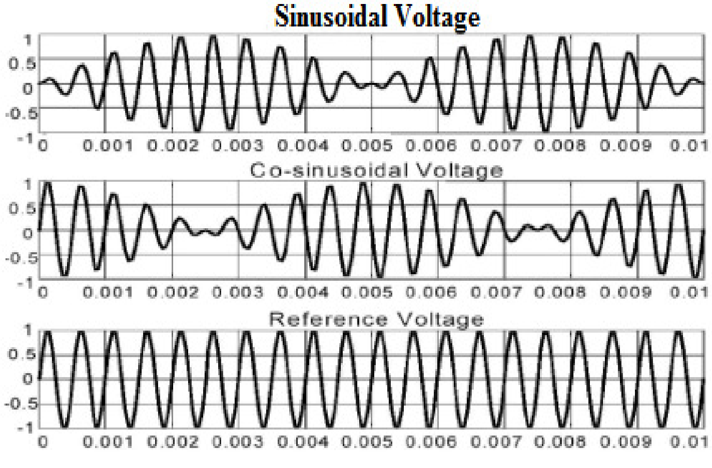


Figure 4.11: Excitation and Output Signal of the Resolver

The shaft angle can be determined by an Inverse Tangent (Bose) function of the quotient of the sampled resolver output voltages $V_{\sin}$, $V_{\cos}$. This determination can be expressed, in terms of resolver output voltages, as follows:

$$\theta = \alpha \tan(\frac{U_{\sin}}{U_{\cos}})$$

4.6 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.

4.6.1 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 (Tiwari). Figure 2.10 shows a voltage source inverter. The AC voltage frequency can be variable or constant depending on the application.

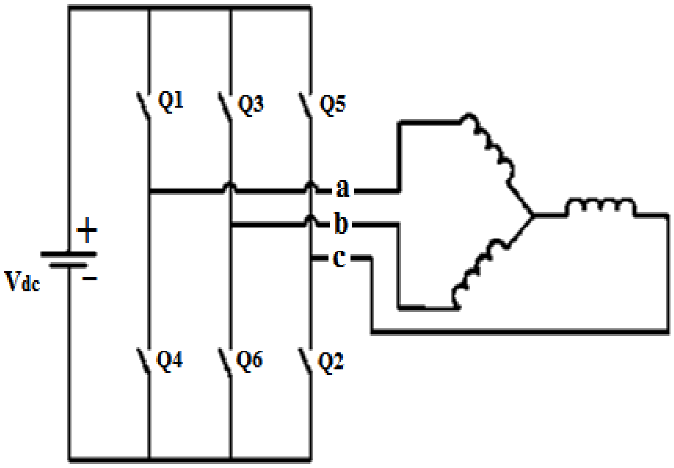


Figure 4.12: Voltage Source Inverter Connected to a Motor

Three phase inverters consist of six power switches connected as shown in figure 4.11 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 are shown in table 4.1 MOSFETs and IGBTs are preferred by industry because of the MOS gating permits high power gain and control advantages. 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 anti-parallel diodes when the switch is turned off. Inverters with anti-parallel diodes are shown in figure 4.12.

Table 4.1: Devices power and Switching Capabilities

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

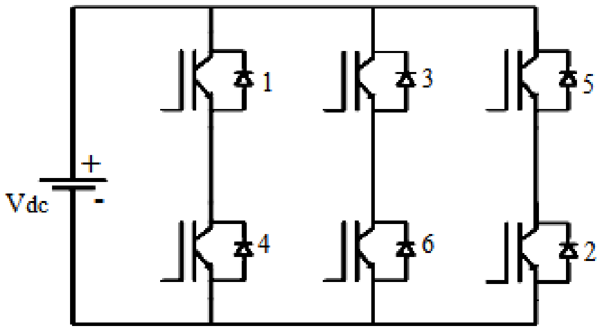


Figure 4.13: Inverter with IGBTs and Anti-parallel Diodes

4.6.2 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. Figure 4.14 shows the characteristic plot of the device.

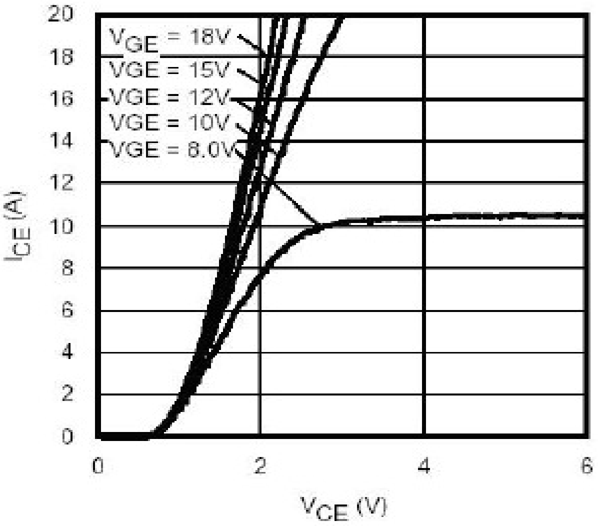


Figure 4.14: Typical IGBT Output Characteristics

The symbolic representation and the equivalent circuit of an IGBT are shown in figure 4.15.

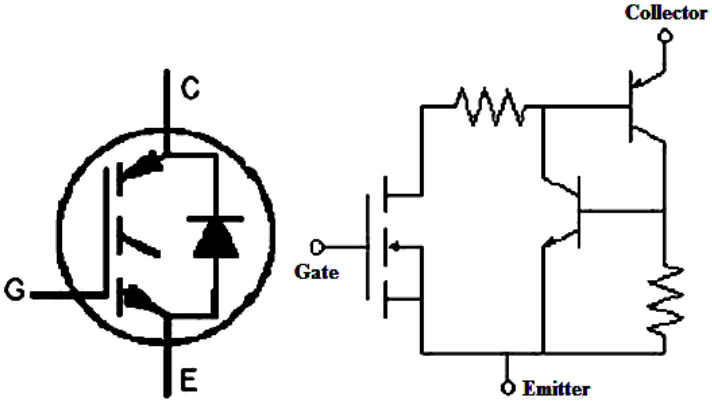


Figure 4.15: IGBT Symbol and Equivalent Circuit

4.6.3 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 bellow.

4.6.3.1 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 are 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 4.16. 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 super-imposed (Tiwari).

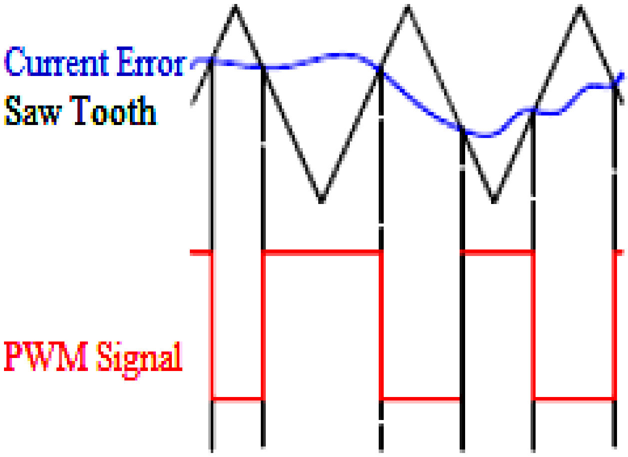


Figure 4.16: PWM current controller

4.6.3.2 HYSTERESIS CURRENT CONTROLLER

Hysteresis current controller can also be implemented to control the inverter currents.

The controller will generate the reference currents with 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 4.17 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 (Pillay, Tiwari).

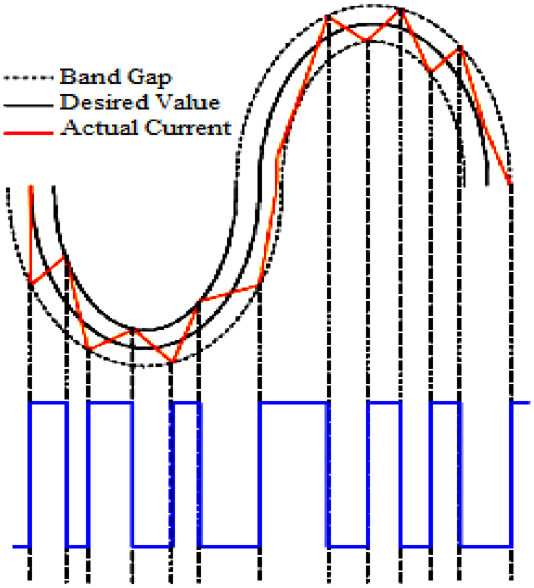


Figure 4.17: Hysteresis controller

4.7 CLOUSER

Thus, this chapter describes the permanent magnet synchronous motor drive system, classification of permanent magnet motors, permanent magnet materials and operation of two current control techniques namely Hysteresis and PWM current controllers.

CHAPTER 5

MODELING OF PM DRIVE SYSTEM

5.1 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.

5.2 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 5.1.

At any time t, the rotating rotor d-axis makes and angle θ_r 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.

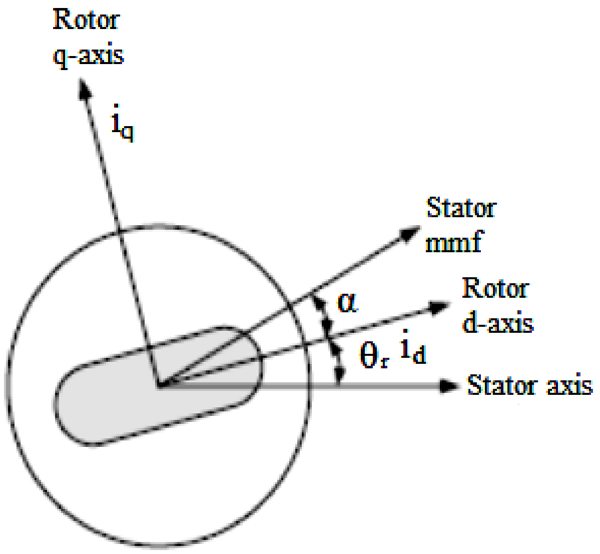


Figure 5.1 Motor Axis

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:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \qquad 5.1$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \qquad 5.2$$

Flux Linkages are given by

$$\lambda_q = L_q i_q \qquad 5.3$$

$$\lambda_d = L_d i_d + \lambda_f \qquad 5.4$$

Substituting equations 5.3 and 5.4 into 5.1 and 5.2

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_q i_q \qquad 5.5$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho(L_d i_d + \lambda_f) \qquad 5.6$$

Arranging equations 5.5 and 5.6 in matrix form

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \qquad 5.7$$

The developed torque motor is being given by

$$T_e = \frac{3}{2} \left(\frac{P}{2}\right) (\lambda_d i_q - \lambda_q i_d) \qquad 5.8$$

The mechanical Torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad 5.9$$

Solving for the rotor mechanical speed form equation 5.9

$$\omega_m = \int \left(\frac{T_e - T_L - B\omega_m}{J}\right) dt \quad 5.10$$

And

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \quad 5.11$$

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

5.3 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 (Bose).

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

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad 5.12$$

Convert Vdqo to Vabc

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \quad 5.13$$

5.3.1 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 5.2 is obtained.

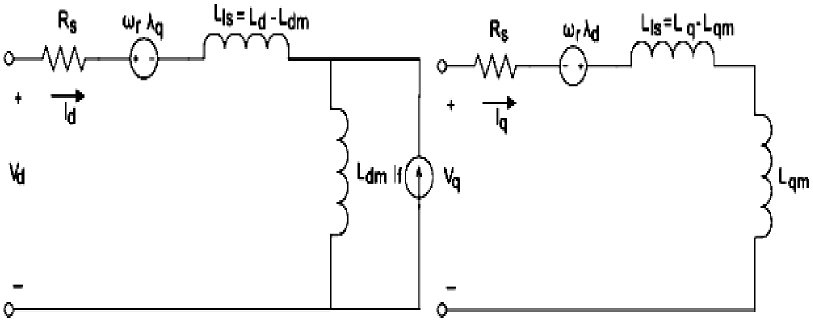


Figure 5.2 Permanent Magnet Motor Electric Circuit without Damper Windings

5.4 PM MOTOR CONTROL

Control of PM motors is performed using field oriented control for the operation of synchronous motor as a dc motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor as shown in figure 5.3.

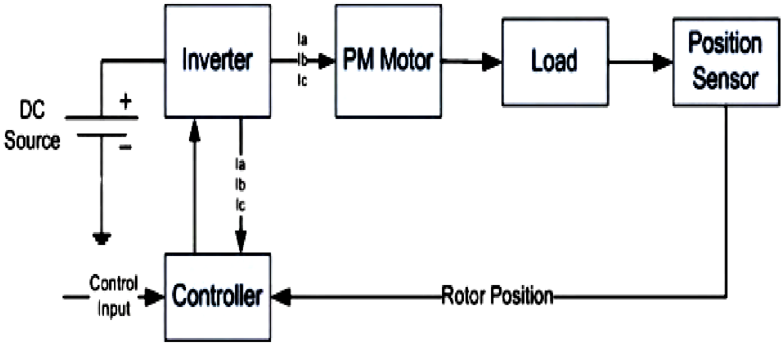


Figure 5.3: Self Control Synchronous Motor

Field oriented control was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective. In order for the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor, at which speed the constant torque operation finishes and the flux weakening starts as shown in figure 5.4.

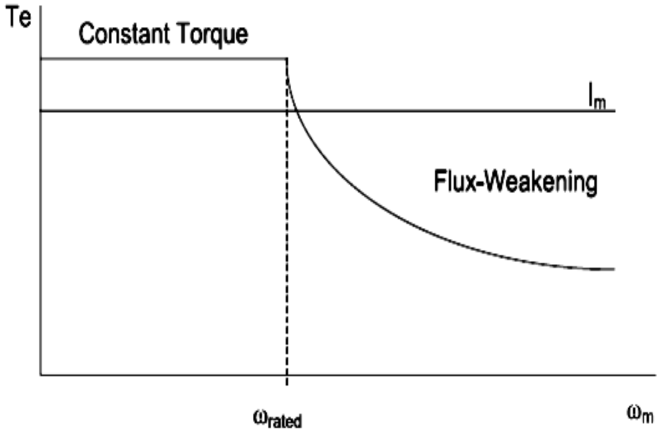


Figure 5.4 Steady State Torque versus Speed

5.4.1 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:

$i_a = I_m \sin(\omega_r t + \alpha)$ 5.14

$i_b = I_m \sin(\omega_r t + \alpha - \frac{2\pi}{3})$ 5.15

$i_c = I_m \sin(\omega_r t + \alpha + \frac{2\pi}{3})$ 5.16

Writing equations 5.14 to 5.16 in the matrix form:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\omega rt + \alpha) \\ \cos(\omega rt + \alpha - \frac{2\pi}{3}) \\ \cos(\omega rt + \alpha + \frac{2\pi}{3}) \end{bmatrix} (I_m) \qquad 5.17$$

Where α is the angle between the rotor field and stator current phasor, ω_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 ω_r, using Park's transformation. The q and d axis currents are constants in the rotor reference frames since α 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 equation 5.17 and 5.12 is obtain id and i_q in terms of I_m as follows

$$\begin{pmatrix} i_q \\ i_d \end{pmatrix} = I_m \begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix} \qquad 5.18$$

Using equations 5.1, 5.2, 5.8 and 5.18 the electromagnetic torque equation is obtained as given below.

$$T_e = \frac{3}{2}\frac{P}{2}\left[\frac{1}{2}\,(L_d - L_q) I_m^2 \sin 2\alpha + \lambda_f I_m \sin\alpha\right] \qquad 5.19$$

5.4.1.1 CONSTANT TORQUE OPERATION

Constant torque 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 iq equal to the supply current Im. That results in selecting the α angle to be 90º degrees according to equation 5.18. By making the id current equal to zero the torque equation can be rewritten as:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f i_q \qquad 5.20$$

Assuming that:

$$K_t = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f \qquad 5.21$$

The torque is given by:

$$T_e = k_t\, i_q \qquad 5.22$$

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

5.4.1.2 FLUX-WEAKENING

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 (Krishnan). The rotor flux of PMSM is generated by permanent magnet which cannot be directly reduced as induction motor. The principle of flux-weakening control of PMSM is to increase negative direct axis current and use armature reaction to reduce air gap flux, which equivalently reduces flux and achieves the purpose of flux-weakening control (Junfeng).

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 α 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 α can be obtained as:

$$\alpha = \tan^{-1}\left(\frac{i_q}{i_d}\right) \qquad 5.23$$

The current I_m is related to id and i_q by:

$$I_m = \sqrt{i_d^2 + i_q^2} \qquad 5.24$$

5.4.1.3 FLUX-WEAKENING CONTROL REALIZATION

The realization process of equivalent flux-weakening control is as follows,

1) Measuring rotor position and speed ω_r from a sensor which is set in motor rotation axis.
2) The motor at the flux weakening region with a speed loop, Te* is obtained from the PI controller.
3) Calculate Iq* using equation 5.20

$$\left(i_q = \frac{T_e^*}{\left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\alpha_f}\right)$$

4) Calculate Id* using equation:

$$i_d^* = \frac{\alpha_d - \alpha_f}{L_d}$$

5) Calculate α using equation 5.23
6) Using α and rotor position the controller will generate the reference currents as per equation 5.17.
7) Then the current controller makes uses of the reference signals to control the inverter for the desired output currents.
8) The load torque is adjusted to the maximum available torque for the reference speed.

$$T_L = T_{e(rated)} \frac{\omega_{rated}}{\omega_r}$$

5.5 CLOUSER

To analytically predict the drive's performance, a mathematical model of permanent magnet synchronous motor (PMSM) without damper winding on rotor reference frame for industrial process, have been developed with reasonable assumptions, where necessary. A parks transformation and dynamic d-q modeling and Field Oriented Control of PM motors with Constant torque operation and Flux-weakening is also developed.

CHAPTER 6

VECTOR CONTROLLED PMSM DRIVE IN MATLAB/SIMULINK

6.1 INTRODUCTION

This chapter describes the advantages of SIMULINK and different tools available for electrical and electronic systems simulation and then justification is given for selecting SIMULINK for the PMSM system. Block by block an explanation is given for SIMULINK simulation of the drive system.

6.2 ADVANTAGES OF SIMULINK

There are two major advantages to perform simulation rather than actually building the design and testing it. The biggest of these advantages is that it is economical. Designing, building, testing, redesigning, rebuilding, retesting for anything can be an expensive project. Simulations take the building/rebuilding phase out of the loop by using the model already created in the design phase. Most of the time, the simulation testing is cheaper and faster than performing the multiple tests of the design each time. Considering the typical university budget cheaper is usually a very good thing. In the case of an electric thruster the test must be run inside of a vacuum tank. Vacuum tanks are very expensive to buy, run, and maintain. One of the main tests of an electric thruster is the lifetime test, which means that the thruster is running pretty much constantly inside of the vacuum tank for 10,000+ hours. This is pouring money down a drain compared to the price of the simulation.

The second major advantage of a simulation is the level of detail that you can get from a simulation. A simulation can give you results that are not experimentally measurable with our current level of technology. Results such as surface interactions on an atomic level, flow at the exit of a micro electric thruster, or molecular flow inside of a star are not measurable by any current devices. A simulation can give these results when problems such as it's too small to measure, the probe is too big and is skewing the results, and any instrument would turn to a gas at those temperatures come into the conversation. You can set the simulation to run for as many time steps you desire and at any level of detail you desire the only restrictions are your imagination, your programming skills, and your CPU.

6.3 SIMULATION TOOLS

Study of electric motor drives needs the proper selection of a simulation tool. Their complex models need computing tools capable of performing dynamic simulations. Today with the growth in computational power there is a wide selection of software titles available for electrical simulations such as ACSL, ESL, EASY5, and PSCSP are for general systems and SPICE2, EMTP, and ATOSEC5 for simulating electrical and electronic circuits. IESE and SABER are examples of general-purpose electrical network simulation programs that have provisions for handling user-defined modules. SIMULINK® is a toolbox extension of the MATLAB program. It is a program for simulating dynamic systems (Ong).

SIMULINK has the advantages of being capable of complex dynamic system simulations, graphical environment with visual real time programming and broad selection of tool boxes (Araujo). 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 (Araujo). Its graphical interface allows selection of functional blocks, their placement on a worksheet, selection of their functional parameters interactively, and description of signal flow by connecting their data lines using a mouse device. System blocks are constructed of lower level blocks grouped into a single mask able block. SIMULINK simulates analogue systems and discrete digital systems (French).

6.4 SIMULINK SIMULATION OF PMSM DRIVE

The PM motor drive simulation was built in several steps like abc phase transformation to dq variables, calculation torque and speed, and control circuit.

The abc phase transformation to dq variables is built using Parks transformation and for the dq to abc the reverse transformation is used. For simulation purpose the voltages are the inputs and the current are output. Parks transformation used for converting Vabc to Vdqo is shown in figure 6.1 and the reverse transformation for converting Idq to Iabc is shown in figure 6.2.

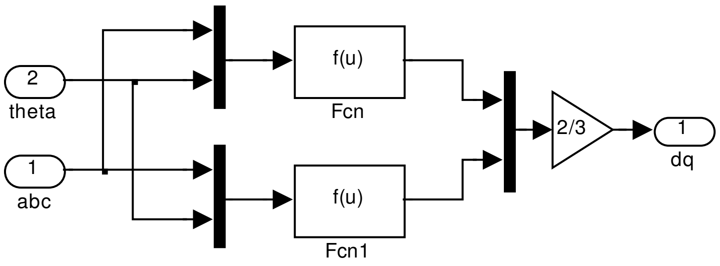


Figure 6.1: abc to dq block

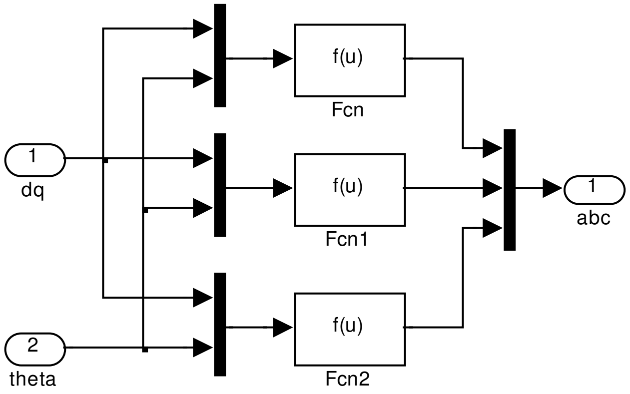


Figure 6.2: dq to abc block

The d and q axis motor circuits built using SIMULINK elements are shown in figure 6.3.

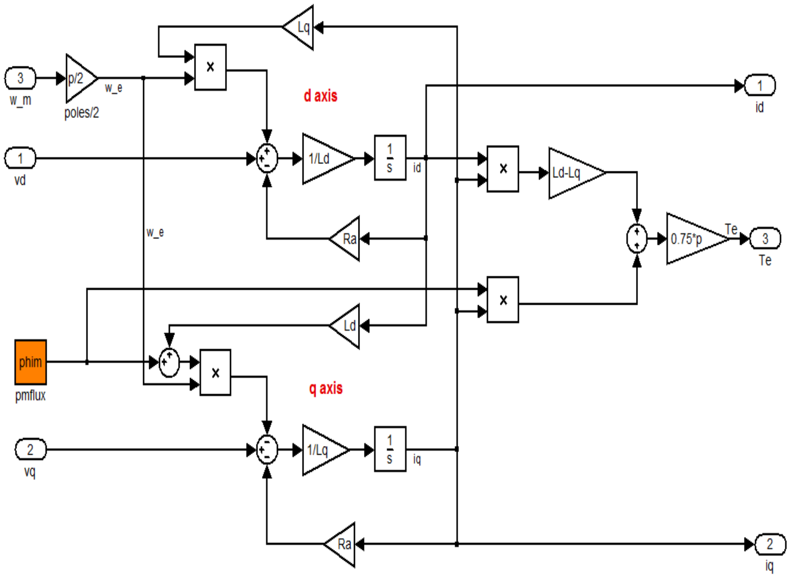


Figure 6.3: PMSM model -- rotor frame of reference (d-axis and q-axis circuit)

Figure 6.4 shows the PMSM Mechanical Model in SIMULINK. This block is developed using equation 5.9 for developing speed.

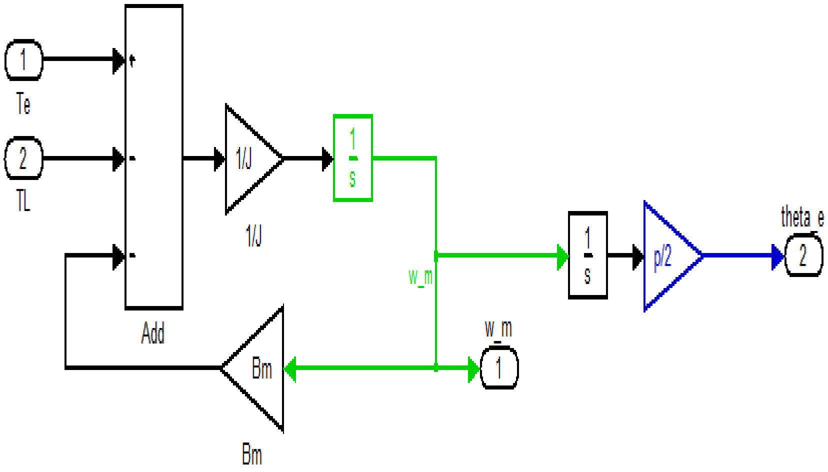


Figure 6.4: PMSM Mechanical Model

Using all the drive system blocks the complete system block (Vector control of PMSM) has been developed as shown in figure 6.5.

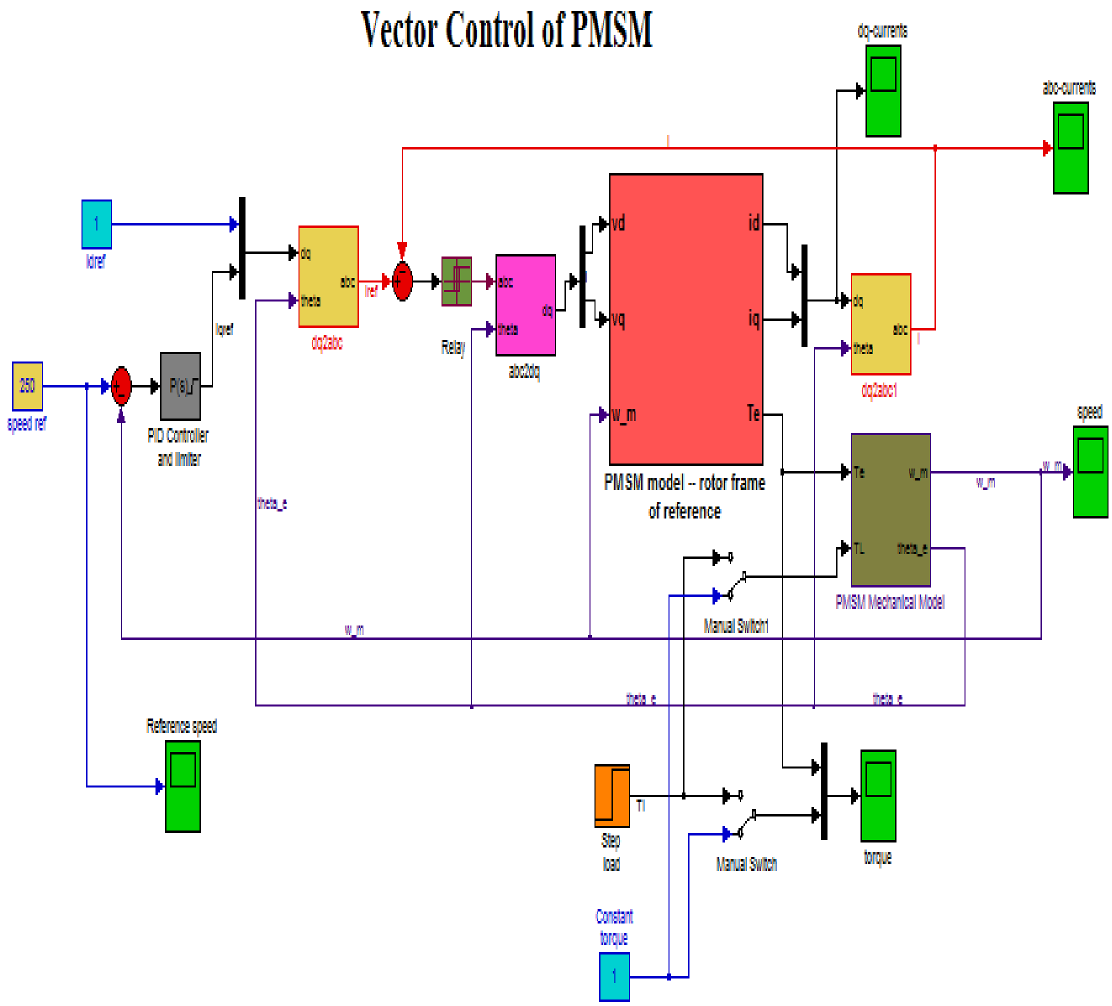


Figure 6.5: Vector control of PMSM in SIMULINK

6.5 CLOUSER

This chapter gives main idea about the blocks converting the three phase variables into two phase variables (abc to dq or reverse parks transformation) and two phase variables into three phase variables (dq to abc or parks transformation), implementing of torque block and the speed block and the speed control of PM motor.

CHAPTER 7

SIMULATION RESULTS

7.1 INTRODUCTION

This chapter deals with the simulation results of PMSM drive system.

The simulation consists of two phases, an accelerating part and a constant speed part. During the accelerating part the motor delivers full torque until it reaches its reference speed, the torque then drops to the same value as the load to keep the speed constant. The simulation also shows a high ripple in both torque and current.

7.2 Case 1

In this the speed and the torque are kept constant. Speed is constant at 175 and load torque TL is constant at 1N.m. Hence below are the waveforms which are obtained from simulation in MATLAB.

7.2.1 Reference Torque and Actual Torque

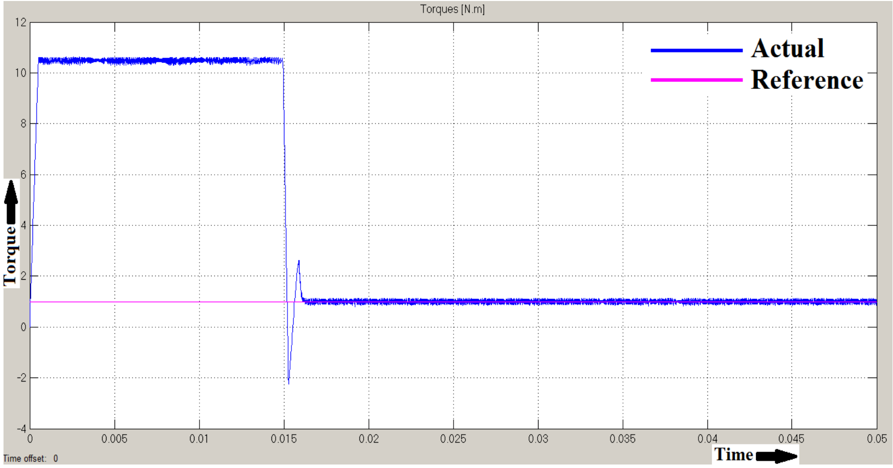
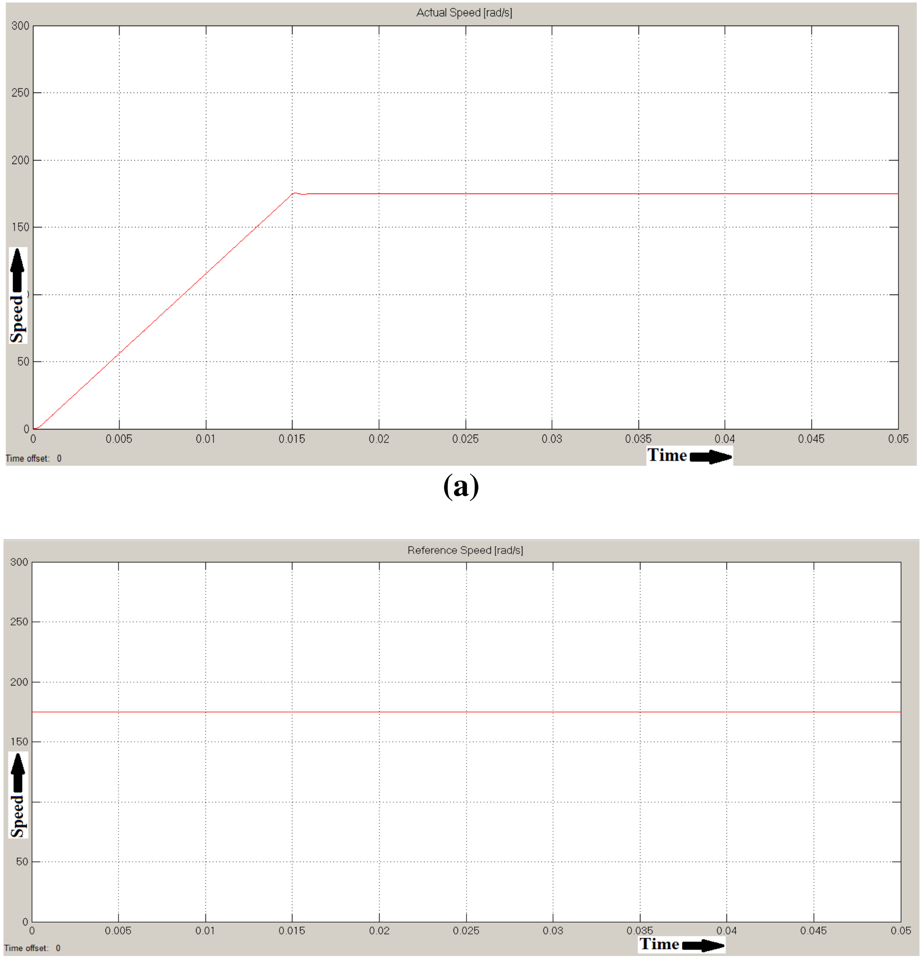


Figure 7.1: Reference torque and actual torque

The above Figure 7.1 waveforms are the simulation result of torque variation which is implemented in MATLAB/SIMULINK. It give information about the variation of actual torque with respective to the reference torque. In this the actual torque first increases up to 10.2N.m till time being of 0.015 after that torque falls and attains the value of -2N.m then at time instant of 0.015 it increases for a while and again falls to follow the reference torque. Hence there is no change in actual torque and reference torque after a time being of 0.016 i.e. torque is not varied after this point of time.

7.2.2 Reference Speed and Actual Speed

The below Figure 7.2 waveforms are the simulation result of speed variation which is implemented in MATLAB/SIMULINK. It give information about the variation of speed with respective to the time. In this the actual speed follows the reference speed after a time being of 0.013 means the motor takes very little time (rise time) of 0.013 to follow the reference speed. Hence under steady state there is no change in actual speed after the rise time i.e. speed is not varied at any point of time.



(a)

(b)

Figure 7.2: (a) Actual speed (b) Reference speed

7.2.3 Three phase currents (ia, ib, ic currents)

The below Figure 7.2 waveforms are the simulation result of current variation which is implemented in MATLAB/SIMULINK. These waveforms are the three phase current in rotating frame of reference under steady state. At the time of starting the three phase current increases up to a value of 10A. After the time period of rise time i.e. 0.015 point of time the three phase current decreases to a value of 1A. From this it is clear that after the rise time the three phase current decreases and remains 10% of the initial value.

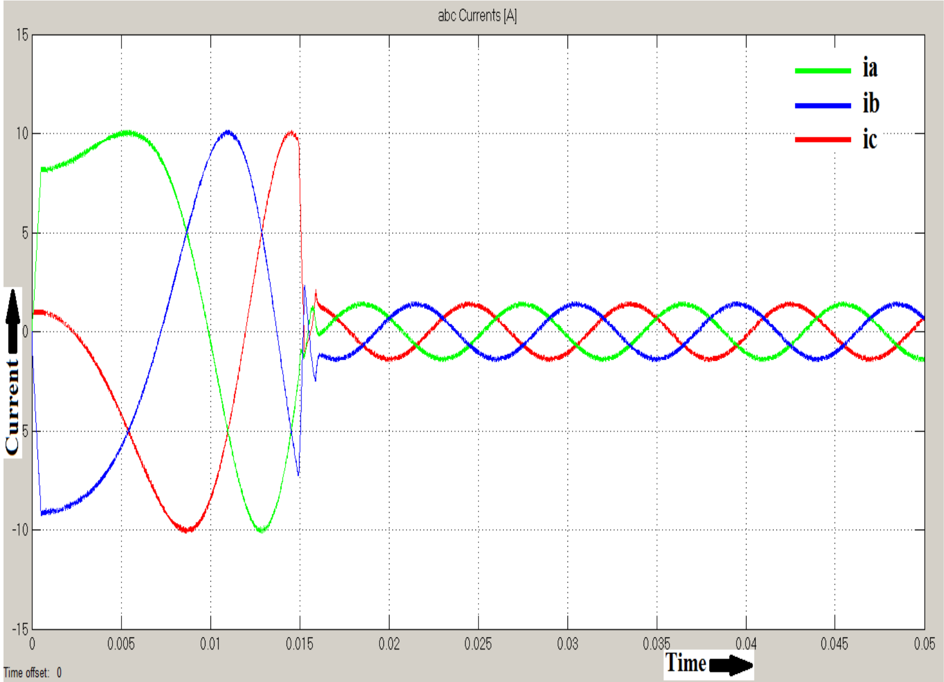


Figure 7.3: Three phase currents

7.2.4 Id current and Iq current

The below Figure 7.4 waveforms are the simulation result of DQ current variation which is implemented in MATLAB/SIMULINK. It give information about the variation of Id and Iq current. The dq current follows the reference and actual torque waveform. As the speed increases and settles down after rise time of 0.015 the Iq current follows the actual torque and Id current follows the reference torque with some fluctuation at 0.016 point of time. After the time being of 0.016 the Id and Iq current becomes constant at a value of 1A.

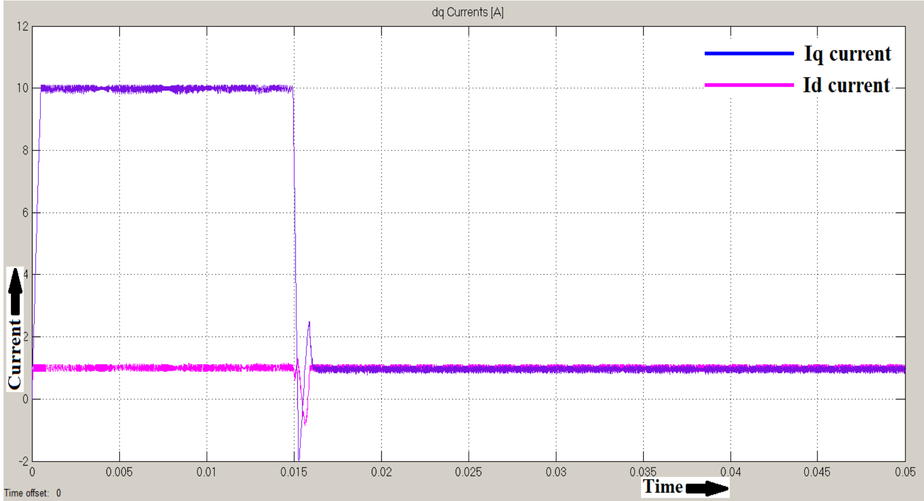
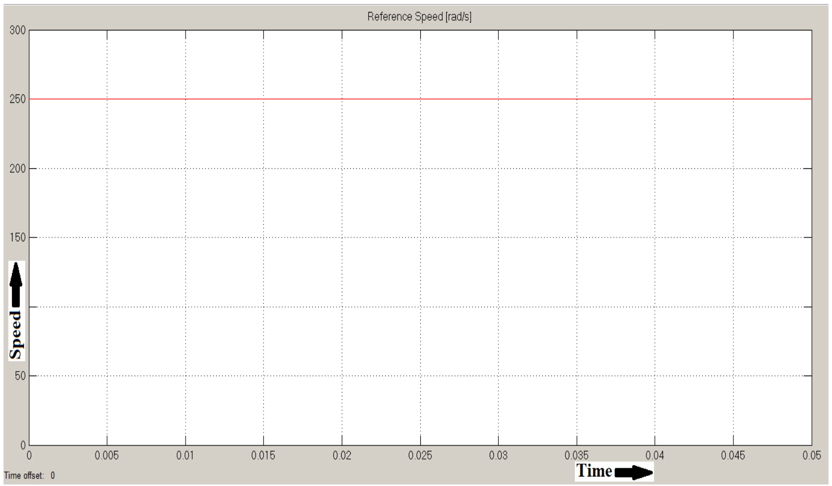


Figure 7.4: Id current and Iq current

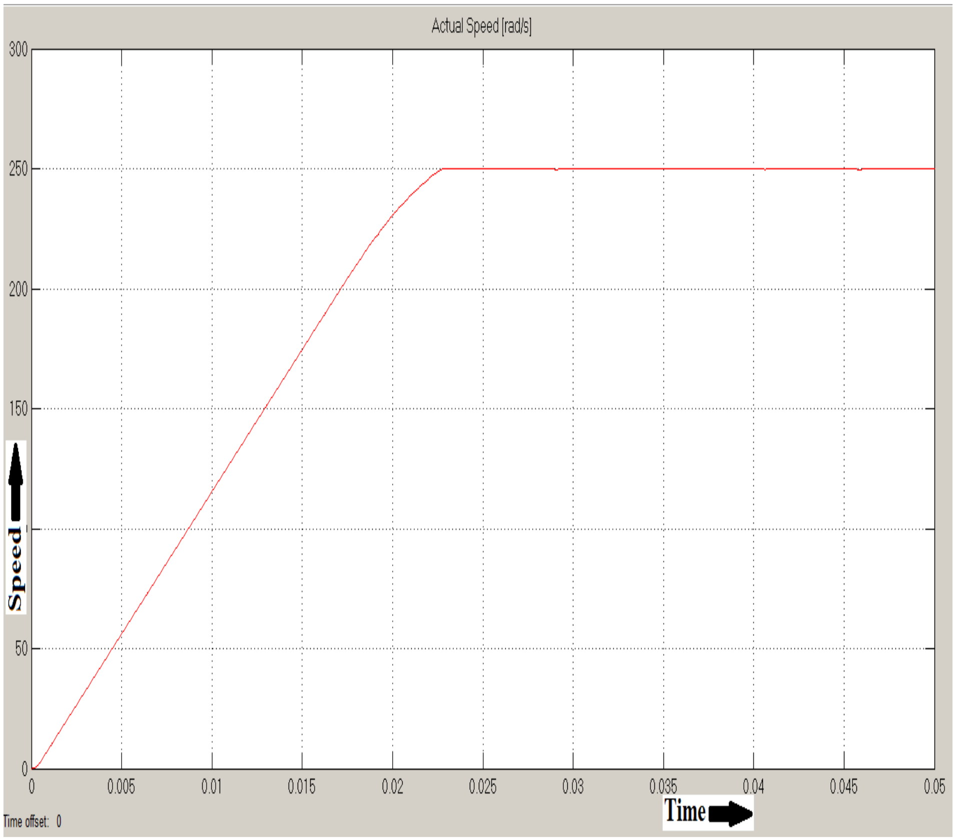
7.3 CASE 2

In this the speed is varied and the torque is kept constant. Speed is varied to a value of 250rpm and load torque TL is constant at a value of 1N.m. Hence below are the waveforms which are obtained from simulation in MATLAB.

7.3.1 Actual Speed and Reference Speed



(a)



(b)

Figure 7.5: (a) Reference speed (b) Actual speed

The above Figure 7.5 waveforms are the simulation result of speed variation which is implemented in MATLAB/SIMULINK. It give information about the variation of speed with respective to the time. In this the actual speed follows the reference speed after a time being of 0.023 means the motor takes very little time (rise time) of 0.023 to follow the reference speed. Hence under steady state there is no change in actual speed after the rise time i.e. speed is not varied at any point of time. In this Figure 7.5 the speed is changed to 250rpm.

7.3.2 Reference Torque and Actual Torque

The below Figure 7.6 waveforms are the simulation result of torque variation which is implemented in MATLAB/SIMULINK. It give information about the variation of actual torque with respective to the reference torque. In this the actual torque first increases up to 10.2A then drops in steps up to a value of 1N.m when the speed attains the constant value of 250 rpm. After this point of time the actual torque follows the reference torque with some fluctuations.

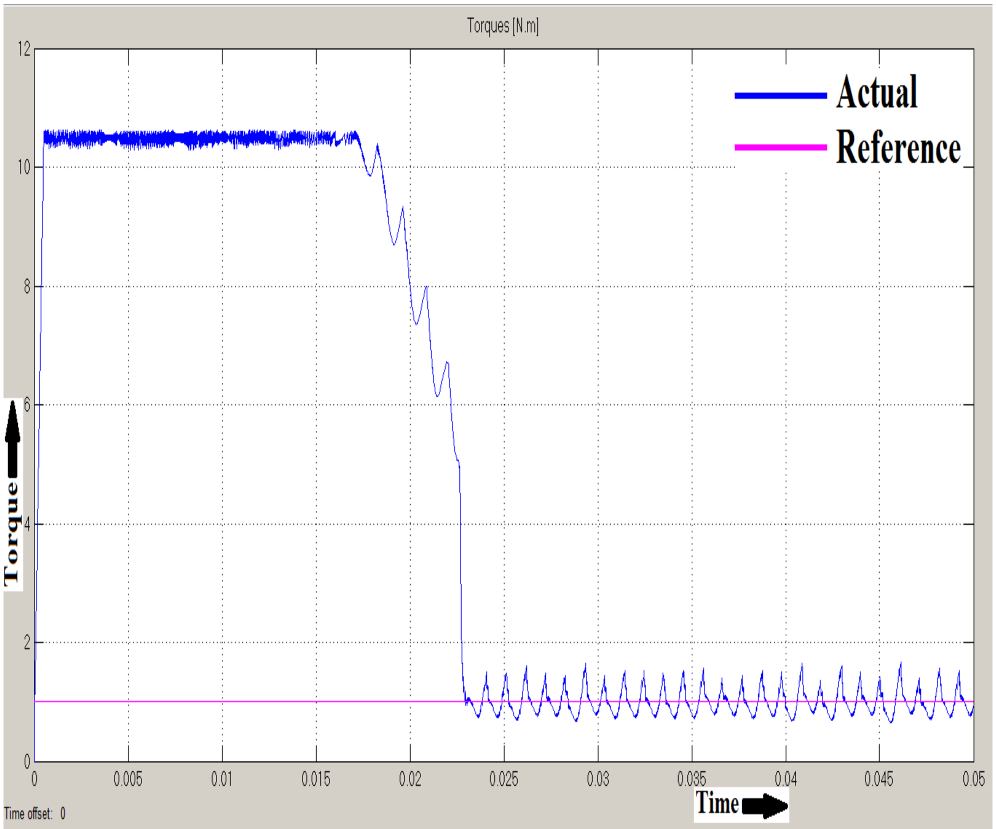


Figure 7.6: Reference torque and actual torque

7.3.3 Three Phase Current (ia, ib, ic currents)

The below Figure 7.7 waveforms are the simulation result of current and voltage variation which is implemented in MATLAB/SIMULINK. These waveforms are the three phase current and voltages in rotating frame of reference under steady state. At the time of starting the three phase current increases up to a value of 10A. After the time period of rise time i.e. 0.015 point of time the three phase current starts decreasing and at a 0.024 point of time the three phase current falls and attains a value of 1A with some fluctuations due to change in speed. From this it is clear that after the rise time the three phase current decreases and remains 10% of the initial value.

The variation of current in the Figure is due to the change in speed.

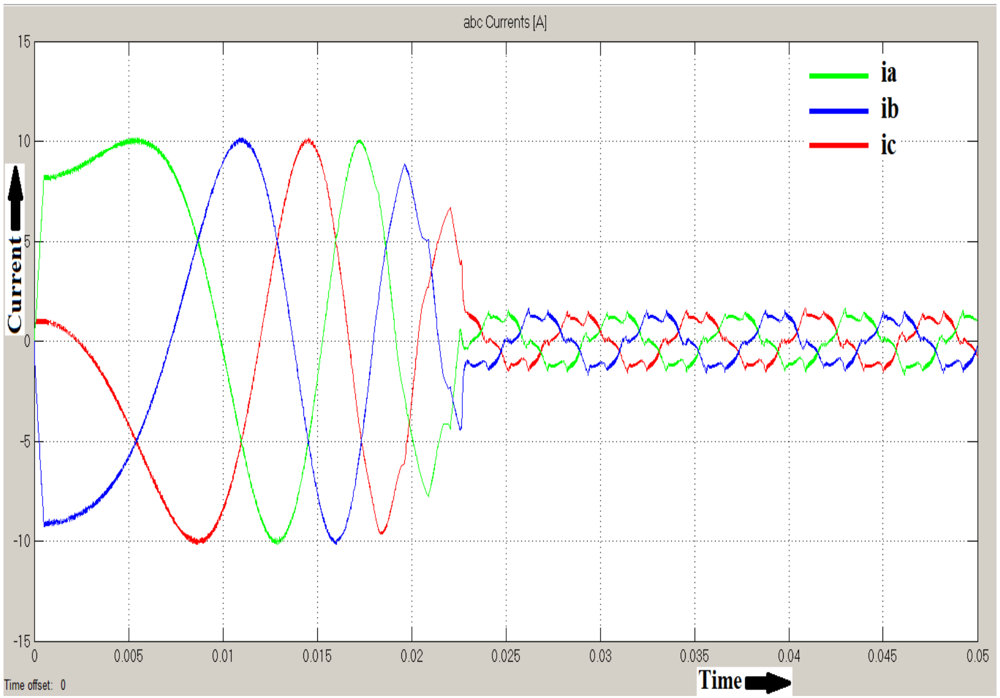


Figure 7.7: Three phase currents

7.3.4 Id current and Iq current

The below Figure 7.8 waveforms are the simulation result of Iq, Id currents which is implemented in MATLAB/SIMULINK. It gives information about the variation of Id current and Iq current. Thus the actual signals which are generated in the control analysis are as shown in the Figure 7.8.

The Id current has some fluctuations from 0.018 to 0.023 when speed increases up to 250 rpm after this point of time the d current becomes zero and follows the reference torque.

The Iq current first increases up to 10A then drop in steps and attains a value of 1A when the speed attains the constant value of 250 rpm. After 0.023 point of time the Id current and Iq current becomes equal and follows the constant current value of 1A with some fluctuation due to change in speed. After this point of time the actual torque follows the reference torque.

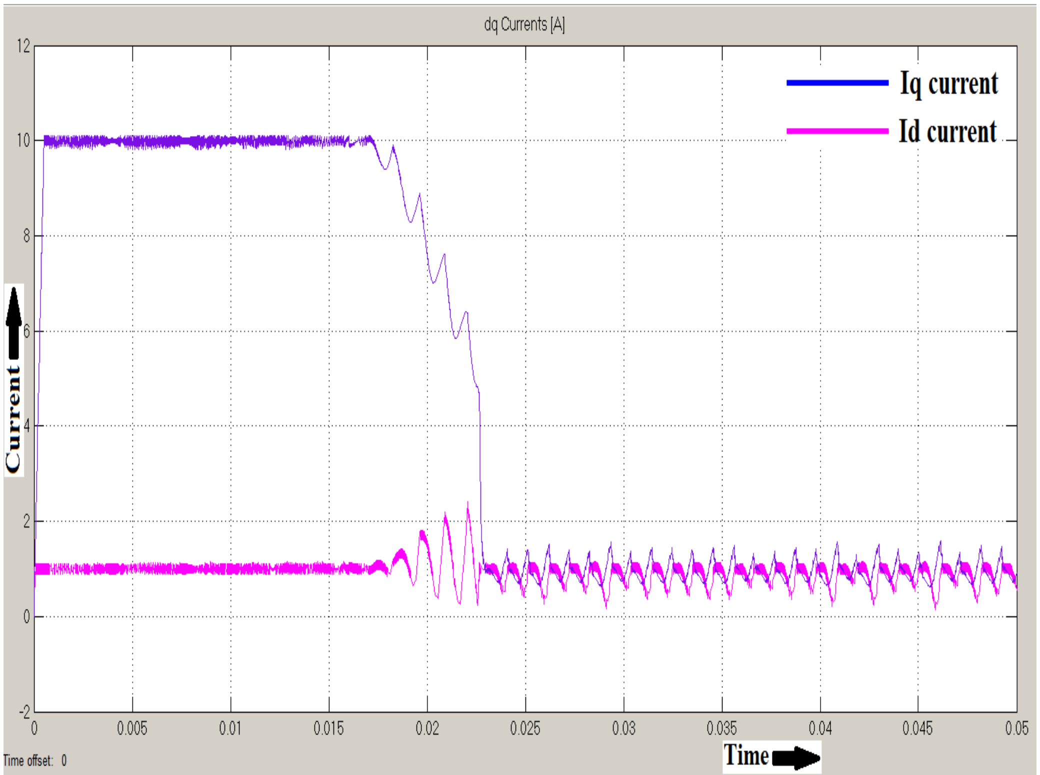


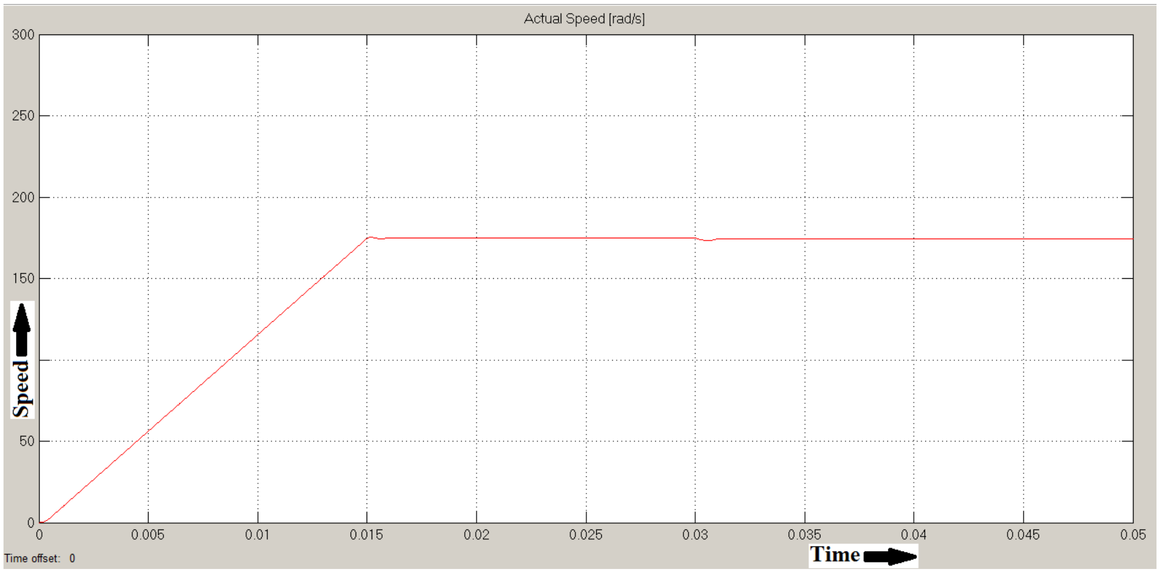
Figure 7.8: Id Current and Iq current

7.4 Case 3

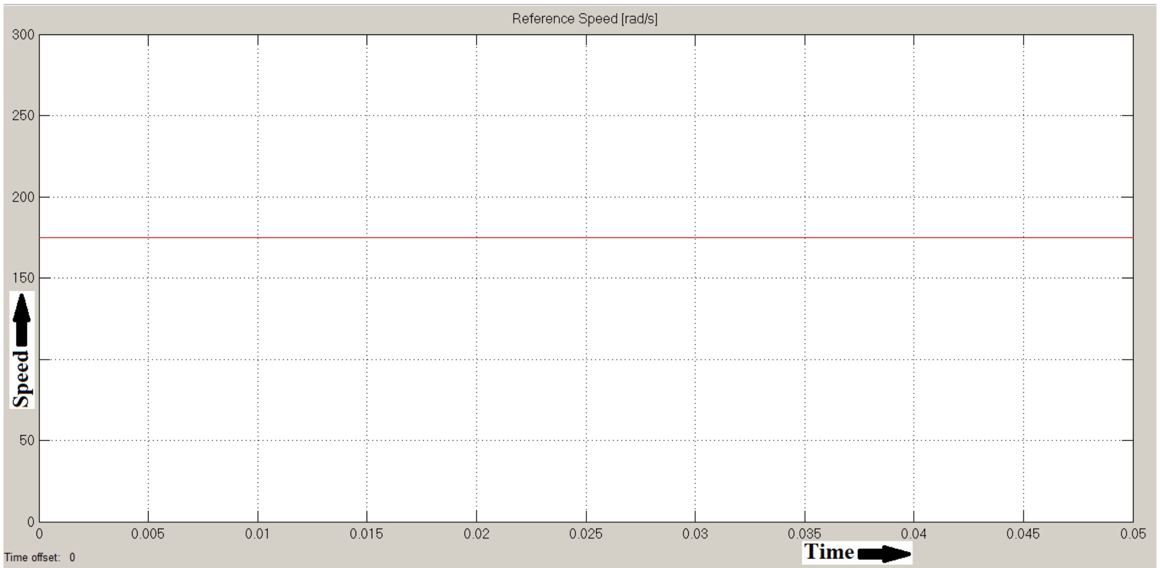
In this the torque is varied and the speed is kept constant. Speed is constant at a value of 175rpm and load torque TL is varied to step load. Hence below are the waveforms which are obtained from simulation in MATLAB.

7.4.1 Actual Speed and Reference Speed

The below Figure 7.9 waveforms are the simulation result of speed variation which is implemented in MATLAB/SIMULINK. It give information about the variation of speed with respective to the time. In this the actual speed follows the reference speed after a time being of 0.015 means the motor takes very little time (rise time) of 0.015 to follow the reference speed. At 0.03 point of time a small dip in speed is seen due to the varied torque. Hence under steady state condition there is no change in actual speed after the rise time i.e. speed is not varied at any point of time.



(a)



(b)

Figure 7.9: (a) Actual speed and (b) Reference speed

7.4.2 Reference Torque and Actual Torque

The below Figure 7.10 waveforms are the simulation result of torque variation which is implemented in MATLAB/SIMULINK. It give information about the variation of torque with respective to the reference torque. In this the actual torque first increases as the speed increases then after the time being of 0.015 the torque falls up to -2N.m after decreasing it starts following the reference torque till 0.03 point of time. Again at 0.03 point of time the actual torque increases up to 8N.m then falls to 5N.m and follows the reference torque. As the reference torque is varied to step torque the actual torque follows reference torque in step. Hence under step torque state the actual torque follows the reference torque in step.

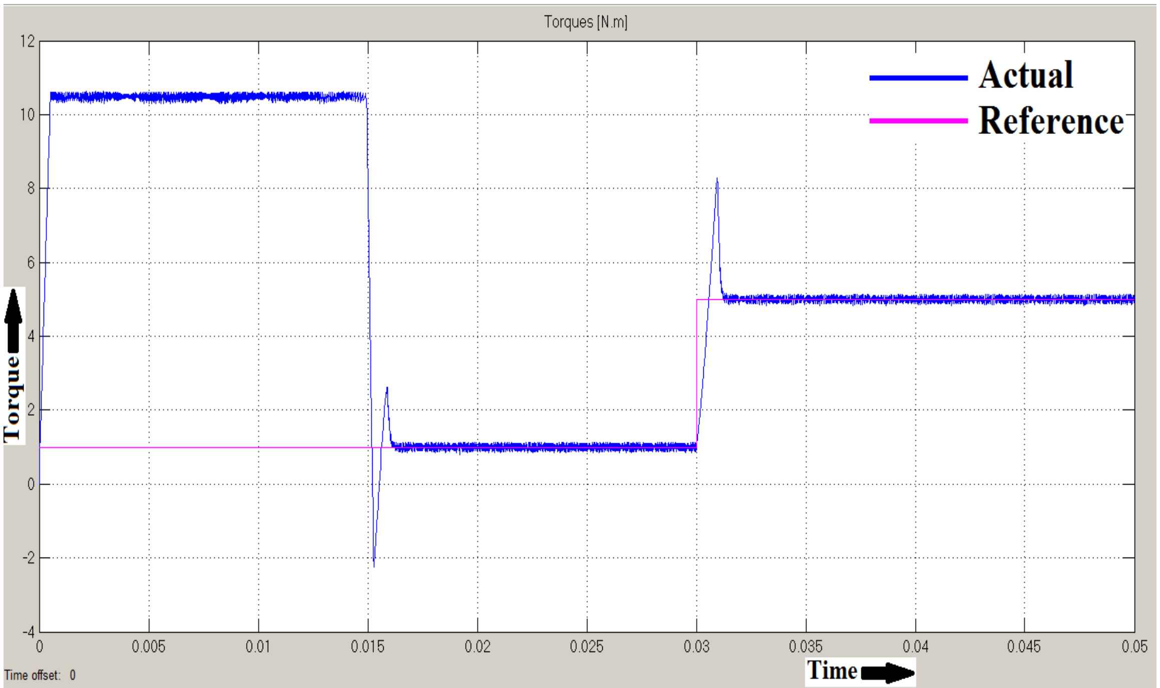


Figure 7.10: Reference torque and actual torque

7.4.3 Three Phase Current (Ia, Ib, Ic Current)

The below Figure 7.11 waveforms are the simulation result of current variation which is implemented in MATLAB/SIMULINK. These waveforms are the three phase current in rotating frame of reference under step torque state. At the time of starting the three phase current increases up to a value of 10A. After the time period of rise time i.e. 0.015 point of time the three phase current decreases to a value of 1A. The three phase current remains at 1A till 0.03 point of time after this the three phase current increases to a value of 5A. From this it is clear that after the rise time the three phase current decreases and remains 10% of the initial value and after 0.03 point of time it decreases and remains 50% of the initial value. Also it increases to 50% of previous value.

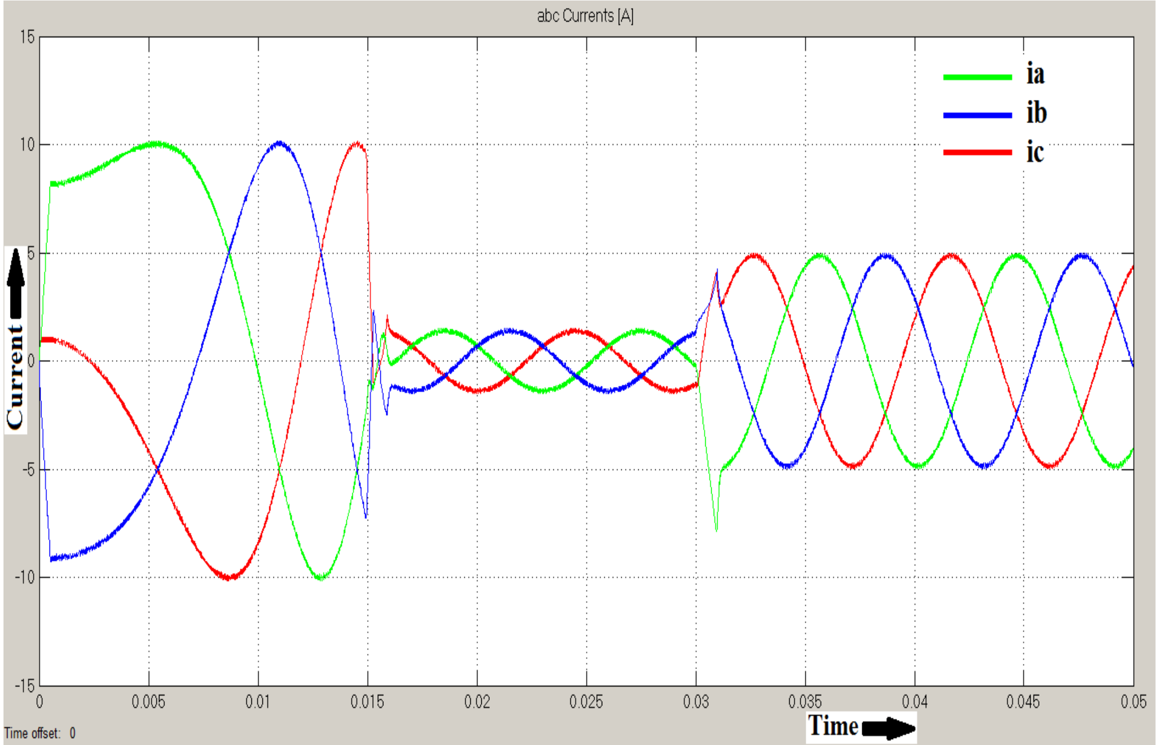


Figure 7.11: Three Phase currents

7.4.4 Iq current and Id current

The below Figure 7.12 waveforms are the simulation result of Iq, Id currents which is implemented in MATLAB/SIMULINK. It gives information about the variation of dq currents. In this the Iq current first increases as the speed increases then after the time being of 0.015 the current falls to -2A and then it increases and follows Id current till 0.03 point of time. After this point of time the Iq current increases to a value of 8A and then falls to 5A.

The Id current remains at 1A and only has ripples when speed attains its constant value of 175rpm and load torque increases.

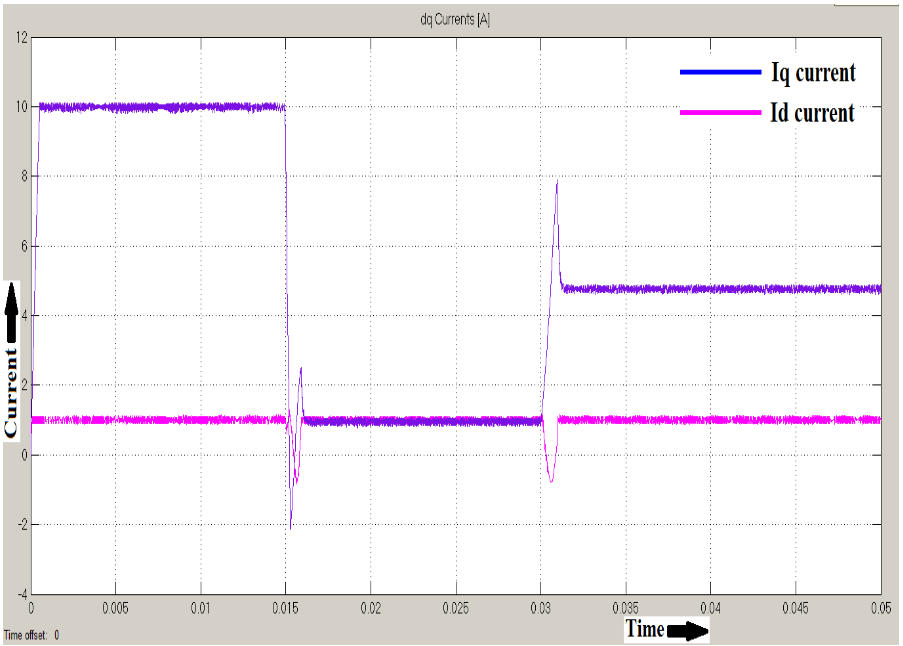
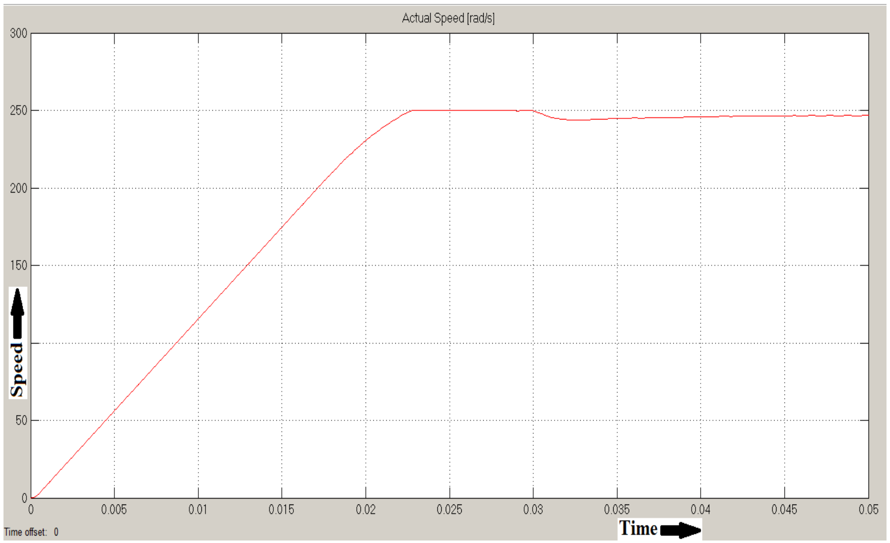


Figure 7.12: Iq current and Id current

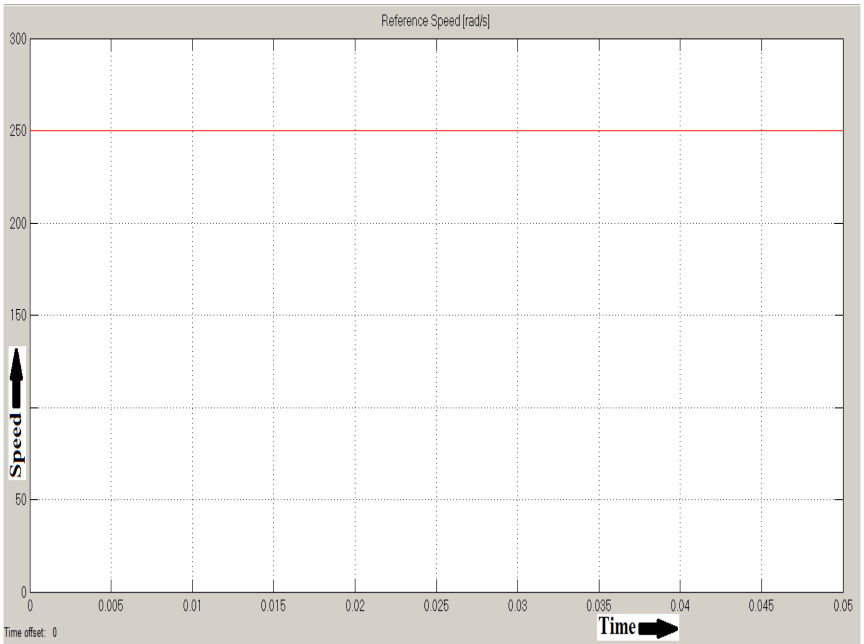
7.5 Case 4

In this both speed and the torque are varied. Speed is constant at a value of 250rpm and load torque TL is varied to step load. Hence below are the waveforms which are obtained from simulation in MATLAB

7.5.1 Actual Speed and Reference Speed



(a)



(b)

Figure 7.13: (a) Actual speed and (b) Reference speed

The above Figure 7.13 waveforms are the simulation result of speed variation which is implemented in MATLAB/SIMULINK. It give information about the variation of speed with respective to time. In this the actual speed rises linearly up to the time of 0.023 after this it settles down to a speed of 250 i.e. follows the reference speed. After some time when the torque is varied a small dip in speed is seen at a 0.03 point of time. Hence speed is not varied at any point of time after 0.04 point of time.

7.5.2 Reference Torque and Actual Torque

The below Figure 7.14 waveforms are the simulation result of torque variation which is implemented in MATLAB/SIMULINK. It give information about the variation of actual torque with respective to the reference torque. In this the actual torque first increases as the speed increases then after the time being of 0.018 the torque falls to 1A and then it has fluctuations due to the change in speed and load torque. After this it follows the reference torque only at interval of 0.023 to 0.03 with some fluctuations.

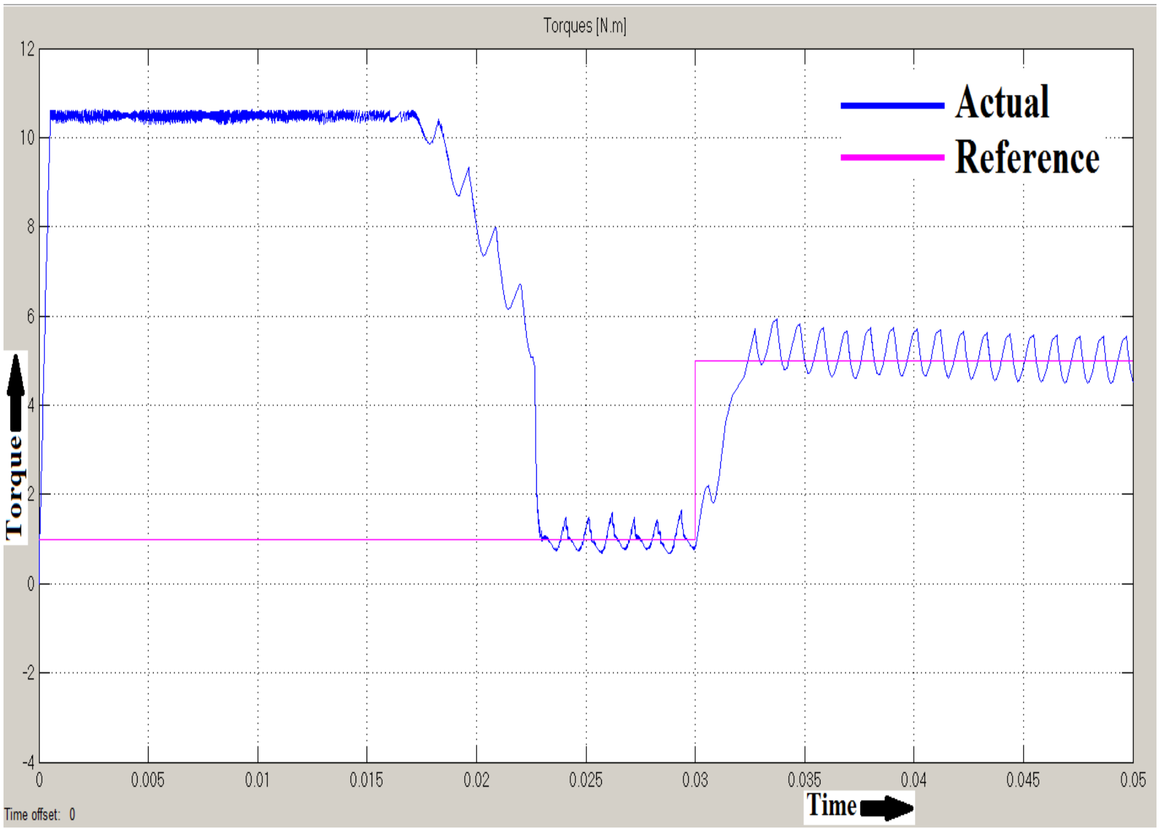


Figure 7.14: Reference Torque and Actual Torque

7.5.3 Three Phase Currents (Ia, Ib, Ic Current)

The below Figure 7.15 waveforms are the simulation result of current variation which is implemented in MATLAB/SIMULINK. These waveforms are the three phase current in rotating frame of reference under step torque state. At the time of starting the three phase current increases to a value of 10A. After the time period of rise time i.e. 0.015 point of time the three phase current decreases to a value of 1A with some fluctuations. The three phase current remains at 1A from 0.023 to 0.03 point of time after this the three phase current increases to a value of 5A with some fluctuations. From this it is clear that after the rise time the three phase current decreases and remains 10% of the initial value and after 0.03 point of time it decreases and remains 50% of the initial value. Also it increases to 50% of previous value.

A ripple is seen in Iabc current at the time when the torque increases and a dip in speed is seen.

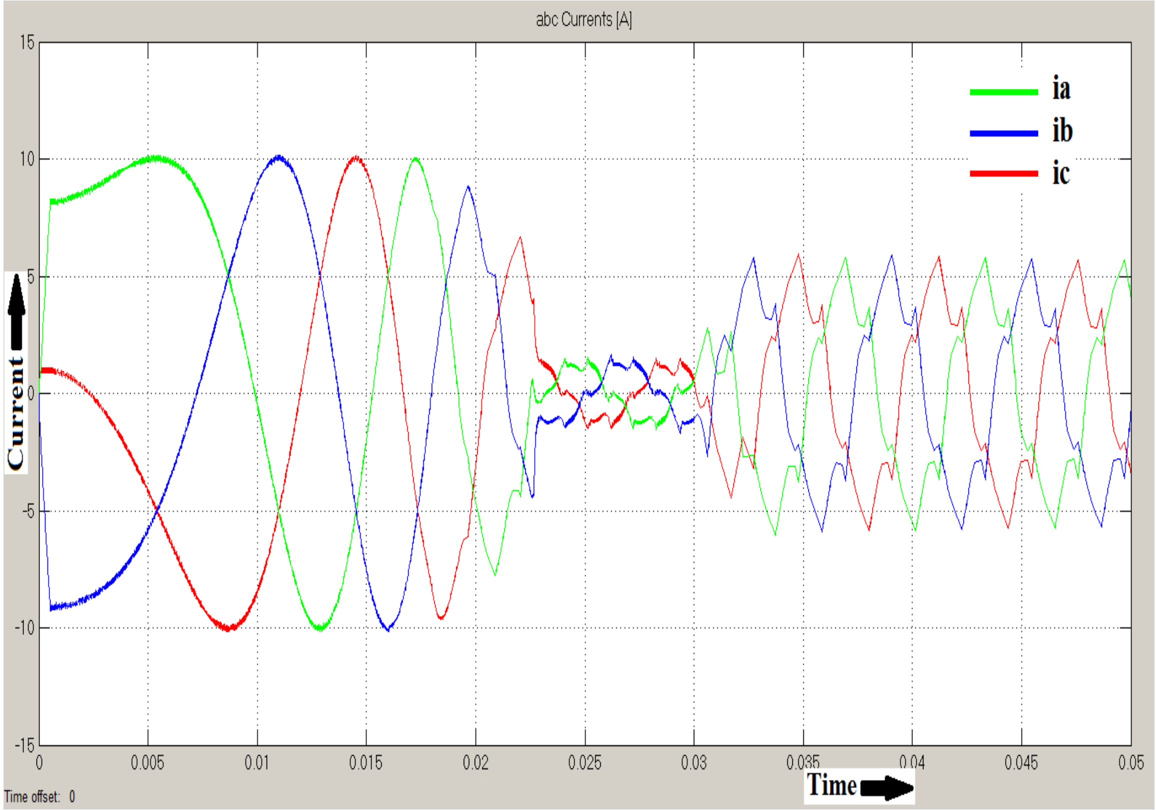


Figure 7.15: Three Phase Currents

7.5.4 Id current and Iq current

The below Figure 7.16 waveforms are the simulation result of Iq, Id currents which is implemented in MATLAB/SIMULINK. It gives information about the variation of dq currents. In this the Iq current first increases as the speed increases then after the time being of 0.018 the torque falls to 1A and has fluctuations due to the change in speed and load torque. After this it follows the Id current only at interval of 0.023 to 0.03 with some fluctuations. After 0.03 point of time the Iq current increases to a value of 5A with some ripples in current.

The Id current remains at 1A it has some fluctuations when speed increases to 250rpm and torque varied. After 0.03 point of time it has ripples due to and torque increases.

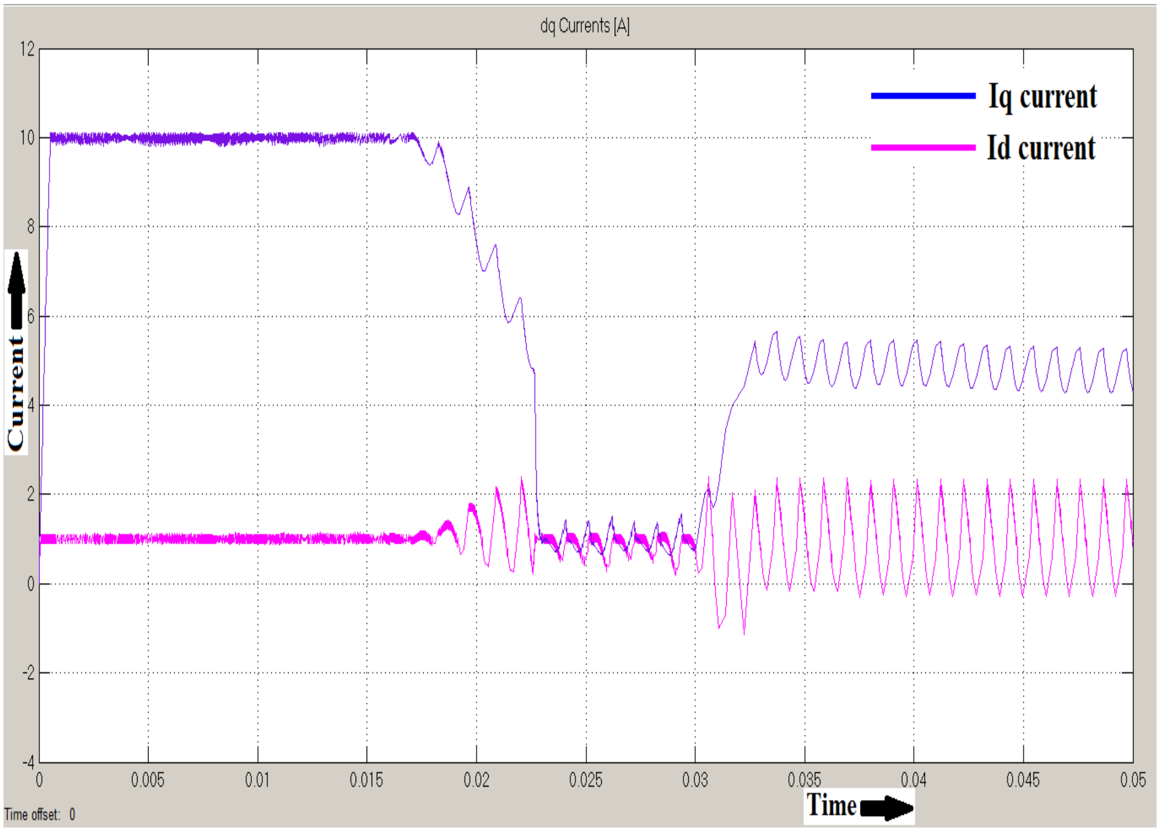


Figure 7.16: Id current and Iq current

7.6 CLOSURE

This chapter presents the individual simulation results for different cases of speed and load torque. The simulation results are analyzed and discussed.

CHAPTER 8

PRACTICAL IMPLEMENTATION OF PMSM DRIVE SYSTEM

8.1 INTRODUCTION

Experimental performance investigations of speed control scheme of IPM based PMSM are presented in this chapter. The speed control in the presence of resolver sensor with vector control scheme is implemented on the PMSM motor. An experimental setup and the performances are analyzed.

8.2 EXPERIMENTAL SETUP

The experimental set up for speed control of PMSM motor in the presence of Resolver sensor for angular position sensing is shown in Figure 8.1. The setup consists of Micro-2407 trainer, Intelligent Power Module (PEC16DSMO1), Inverter module, permanent magnet synchronous motor. The Micro-2407 a 16-bit fixed point DSP trainer based on TMS320LF2407A DSP Processor is used. This trainer has digital control along with basic DSP functions like filtering, PWM generation and calculation of spectral characteristics of input analog signals. The TMS320LF2407A contains a C2xx DSP core along with useful peripherals such as ADC, Timer, and PWM Generation integrated onto a single piece of silicon.

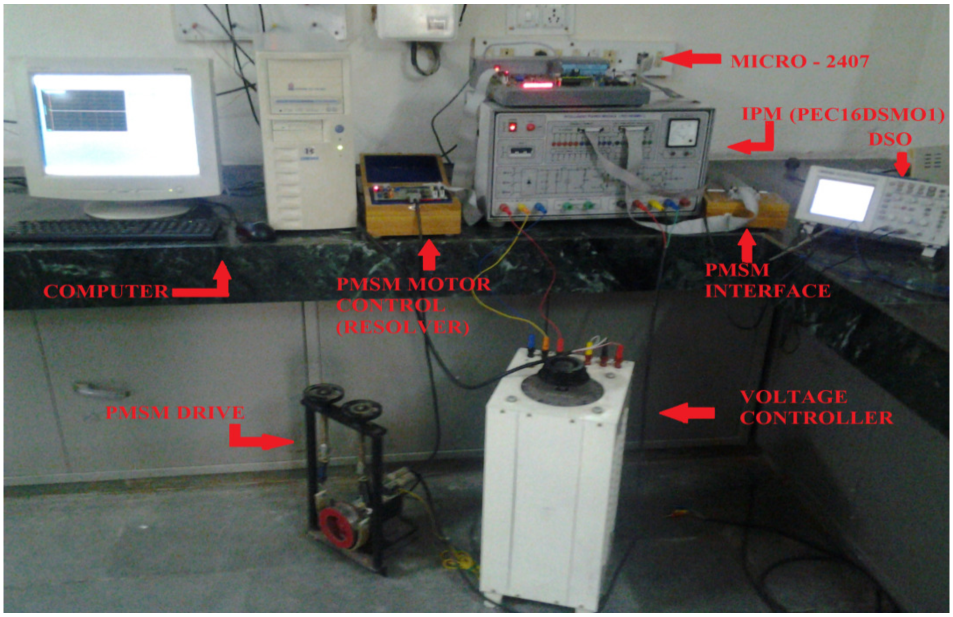


Figure 8.1: Experimental Setup

The Micro-2407 trainer can be operated in two modes.

In the mode: 1(serial mode) the trainer is configured to communicate with PC through serial port.

In the mode: 2 (stand alone mode), the trainer can be interacted rough the IBM PC keyboard and 16 × 2 LCD display.

8.3 RESOLVER SENSOR

Resolvers are obsolete angle transducers are mounted on the motor shaft to get the motor's absolute angular position. The accuracy is typically in the range of 5 arc min. Resolvers are often used for angle sensing in noisy environment, due to their rugged construction and their ability to reject common mode noise.

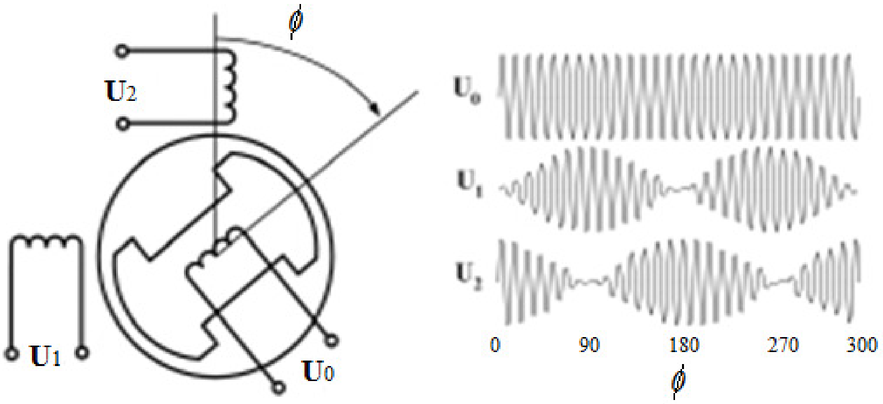


Figure 8.2: Resolver, Simplified Functional Diagram and Corresponding Signals

Resolver consists of two parts an analog resolver and a resolver-to-digital converter (RDC). The analog resolver is basically a two – phase machine that is excited by a rotor mounted field winding, which is excited by a carrier wave with several kHz frequencies from RDC. The resolver is brushless because the rotor winding is excited by a revolving transformer. The stator winding of the resolver gives the amplitude-modulated output as shown in the following equations.

$$V_1 = AV_0 \sin\omega t \sin\theta$$

$$V_2 = AV_0 \sin\omega t \cos\theta$$

Where,

ω = Oscillator frequency

V_0 = Oscillator voltage

A = Effective transformation ratio between the transformer primary and output windings and

θ = Electrical orientation angle of the rotor excitation winding as shown.

8.4 Block Diagram of Field Oriented Control of PMSM Using Resolver Sensor

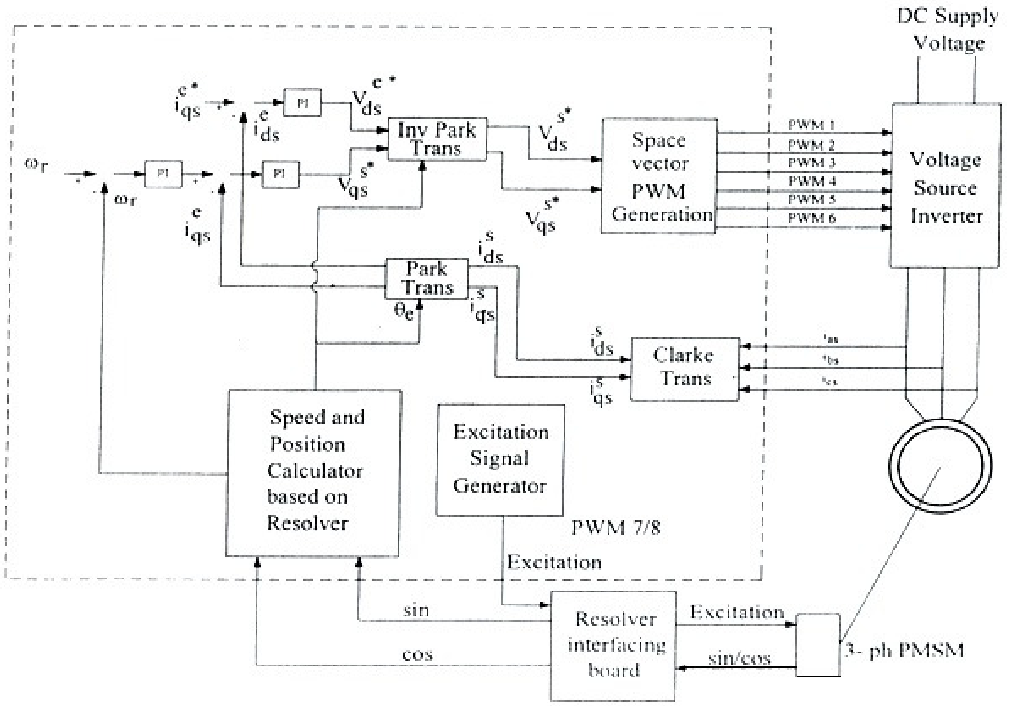


Figure 8.3: Block Diagram of Field oriented Control

The overall system for implementation of the three phase PMSM control can be depicted as shown in figure. The PMSM is driven by the conventional voltage source inverter. The TMS320F2407 is generating six pulse width modulations (PWM) signal by means of space vector PWM technique for six power switching devices in the inverter. Two input currents of the PMSM (i_a and i_b) are measured from the inverter and two resolver signals (i.e. sin and cos) are also measured from the resolver interface board. They are sent to the TMS320F2407 via two analog to digital converters (ADCs).

Theoretically, the field oriented control for the PMSM drive allows the motor torque be controlled independently with the flux like DC motor operation. On other words, the torque and flux are decoupled from each other. The rotor position is required for variable transformation from stationary reference frame to synchronously rotating reference frame. As a result of this transformation (so called Park transformation). q-axis current will be controlling torque while d-axis current is forced to zero. Therefore, the key module of this system is the information of rotor position from resolver sensor.

8.5 CONNECTION DIAGRAM

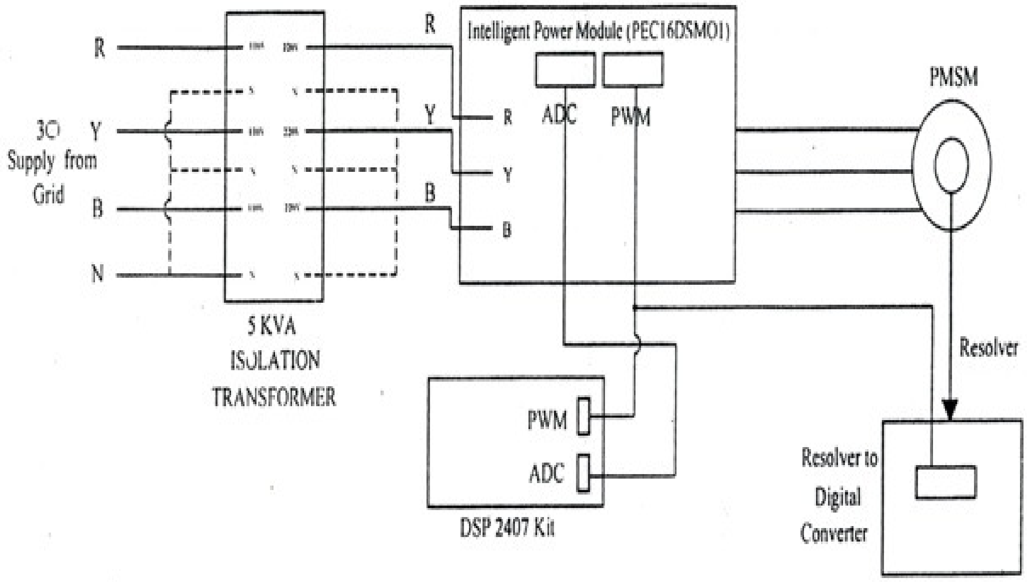


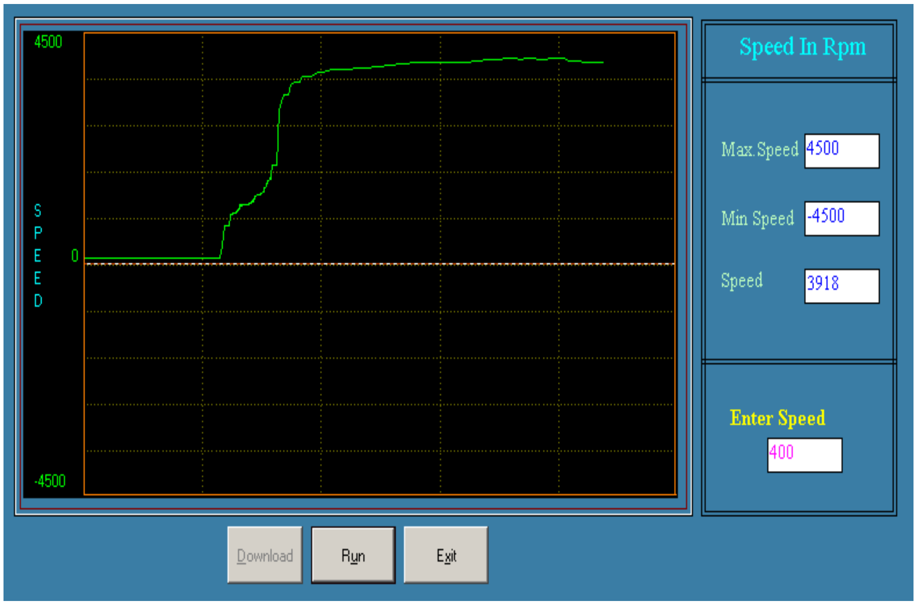
Figure 8.4: Connection Diagram

The three phase supply from grid is given to 5 KVA isolated Transformer as the input of transformer. The output of transformer is treated as input of Intelligent Power Module (PEC16DSN01). The DSP - 2407 kit converts analog signals to digital and gives to IPM and IPM generates PWM signals and gives back to DSP - 2407. Now the IPM analyzes the ADC and PWM signals and gives to PMSM. A resolver is attached to PMSM which converts the signals into digital and feed back to IPM.

8.6 EXPERIMENTAL RESULTS

8.6.1 Increase in Voltage

Speed is increased due to increase in voltage regulator up to 300V. As the voltage increase the speed of motor increases.



Max Speed 4500

Min Speed -4500

Speed 3918

Enter Speed 400

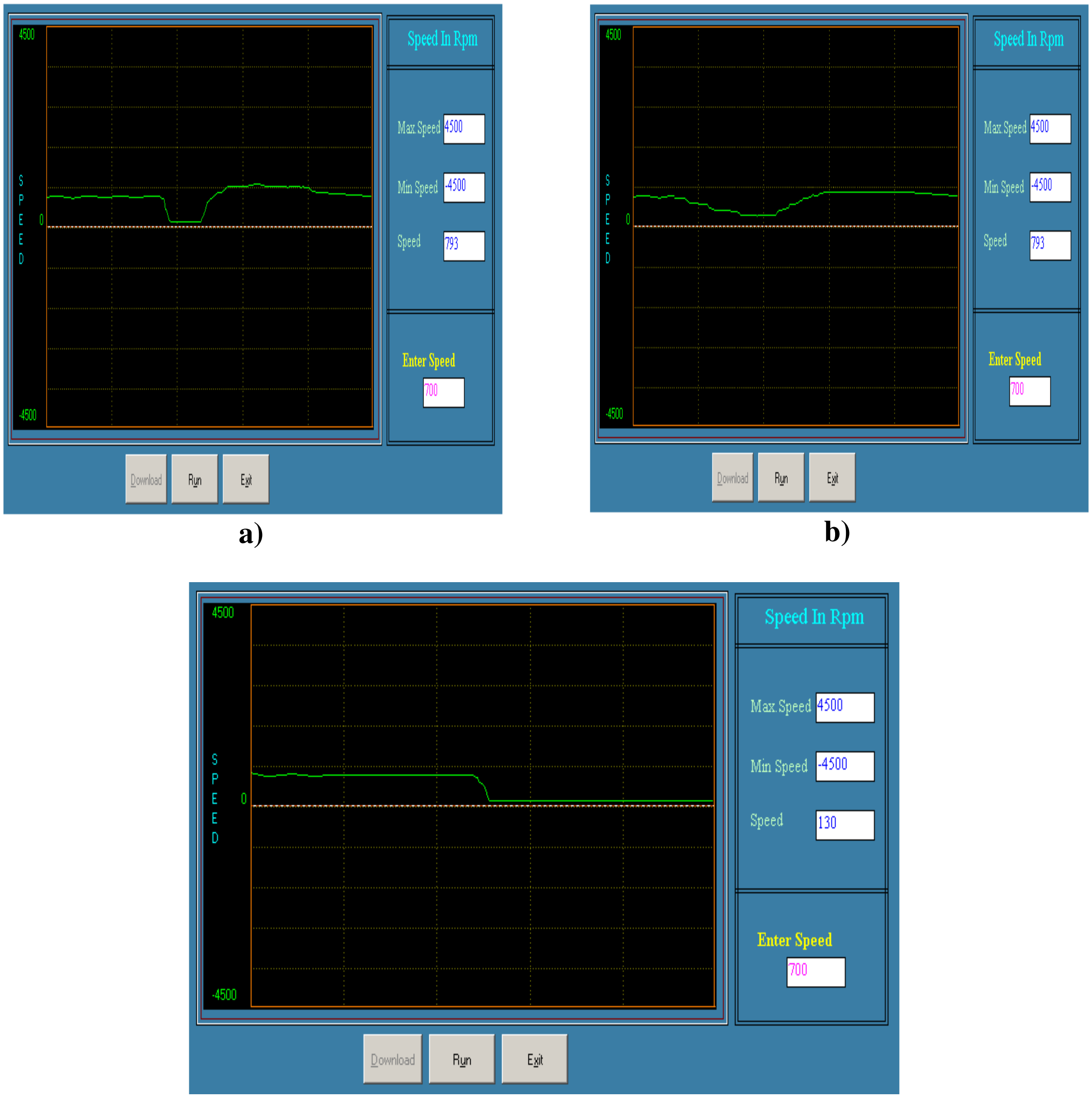
Figure 8.5: Voltage is increased up to 300V

8.6.2 CASE 1: At speed of 700 rpm

When the load increases all of sudden at the speed of 700 rpm, the motor draws more torque due to which a dip in speed is seen after this when the load is released the motor tries to stable at its synchronous speed.

When the load is linearly increased the speed of motor also falls linearly and when the load is removed then motor tries to get back at its synchronous speed.

When full load is applied to motor, the motor speed falls and becomes equivalent to zero and remains at zero unless and until the load is not removed.



Speed In Rpm

Max Speed 4500

Min Speed -4500

Speed 793

Enter Speed 700

a)

Speed In Rpm

Max Speed 4500

Min Speed -4500

Speed 793

Enter Speed 700

b)

Speed In Rpm

Max Speed 4500

Min Speed -4500

Speed 130

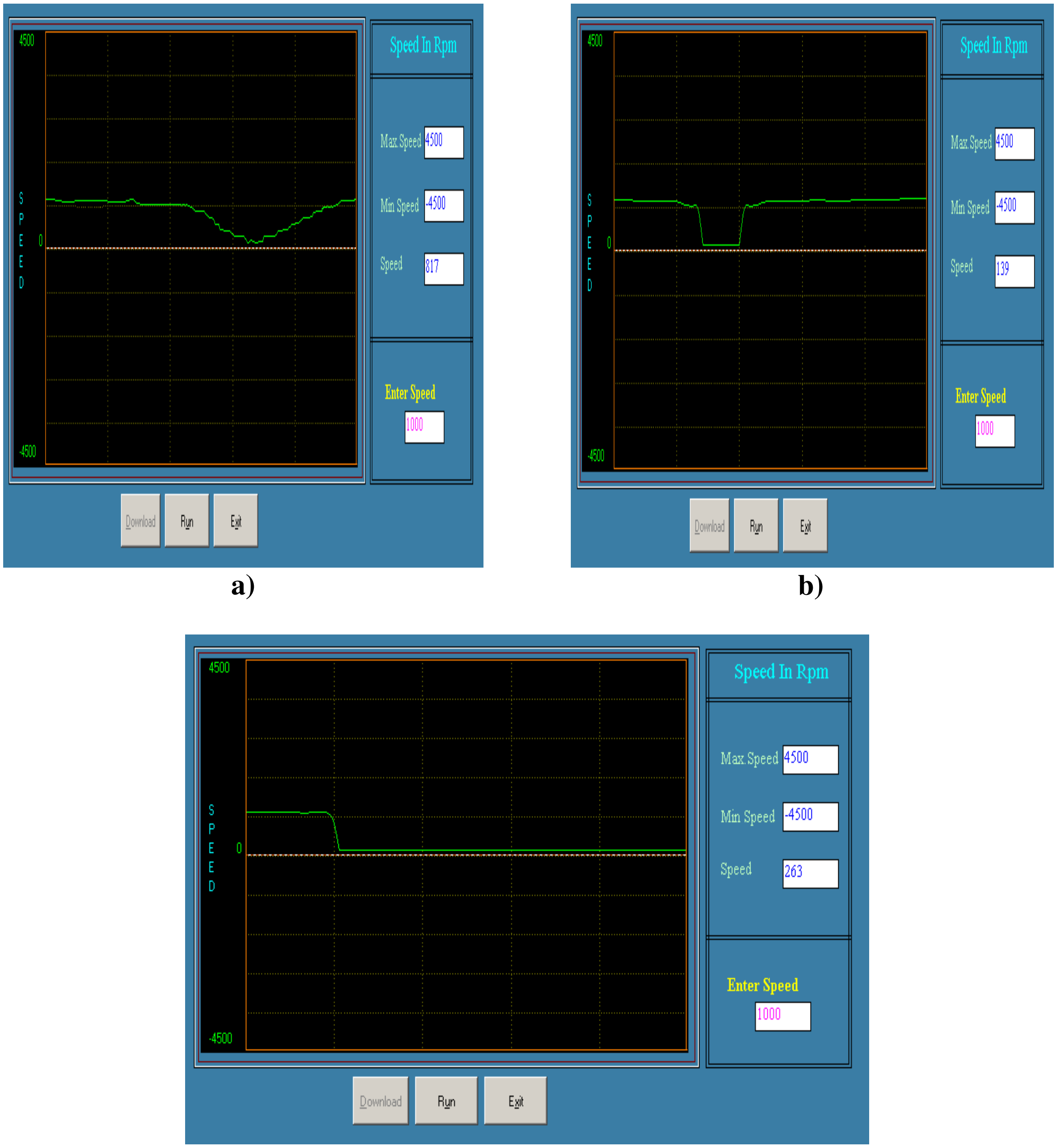
Enter Speed 700

c)

Figure 8.6: Waveforms of different load conditions at a speed of 700 rpm: a) Sudden increase in load, b) Linear Change in Load, c) At full load.

8.6.3 CASE 2: At speed of 1000 rpm

When the load increases all of sudden at the speed of 1000 rpm, the motor draws more torque due to which a dip in speed is seen after this when the load is released the motor tries to stable at its synchronous speed.



Speed In Rpm
Max Speed 4500
Min Speed -4500
Speed 817
Enter Speed 1000

a)

Speed In Rpm
Max Speed 4500
Min Speed -4500
Speed 139
Enter Speed 1000

b)

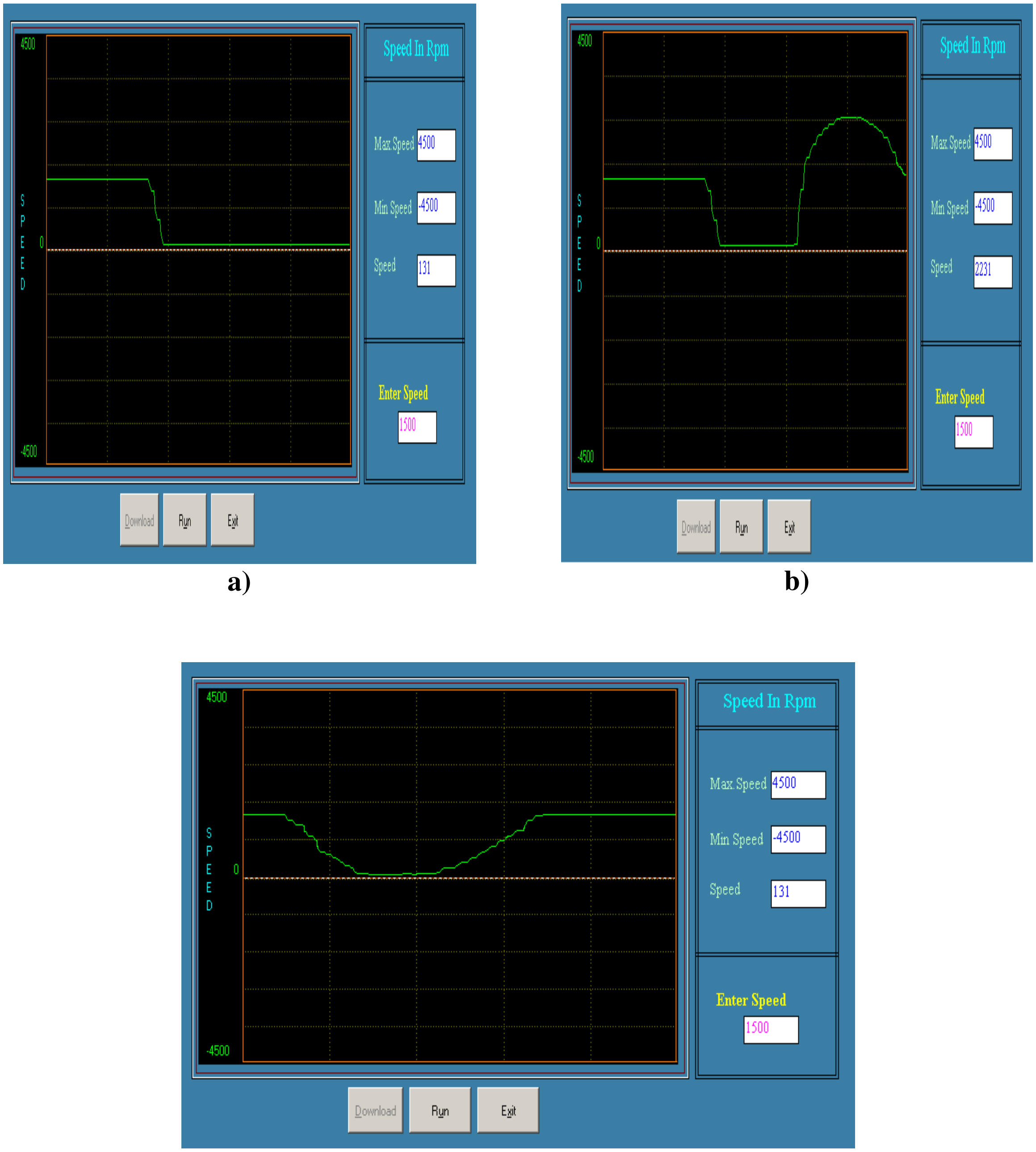
Speed In Rpm
Max Speed 4500
Min Speed -4500
Speed 263
Enter Speed 1000

c)

Figure 8.7: Waveforms of different load conditions at a speed of 1000 rpm: a) Linear Change in Load, b) Sudden increase in load, c) At full load

8.6.4 CASE 3: At a speed of 1500 rpm

When the load increases all of sudden at the speed of 1500 rpm, the motor draws more torque due to which a dip in speed is seen after this when the load is released the motor tries to stable at its synchronous speed.



Max Speed 4500
Min Speed -4500
Speed 131
Enter Speed 1500

a)

Max Speed 4500
Min Speed -4500
Speed 2231
Enter Speed 1500

b)

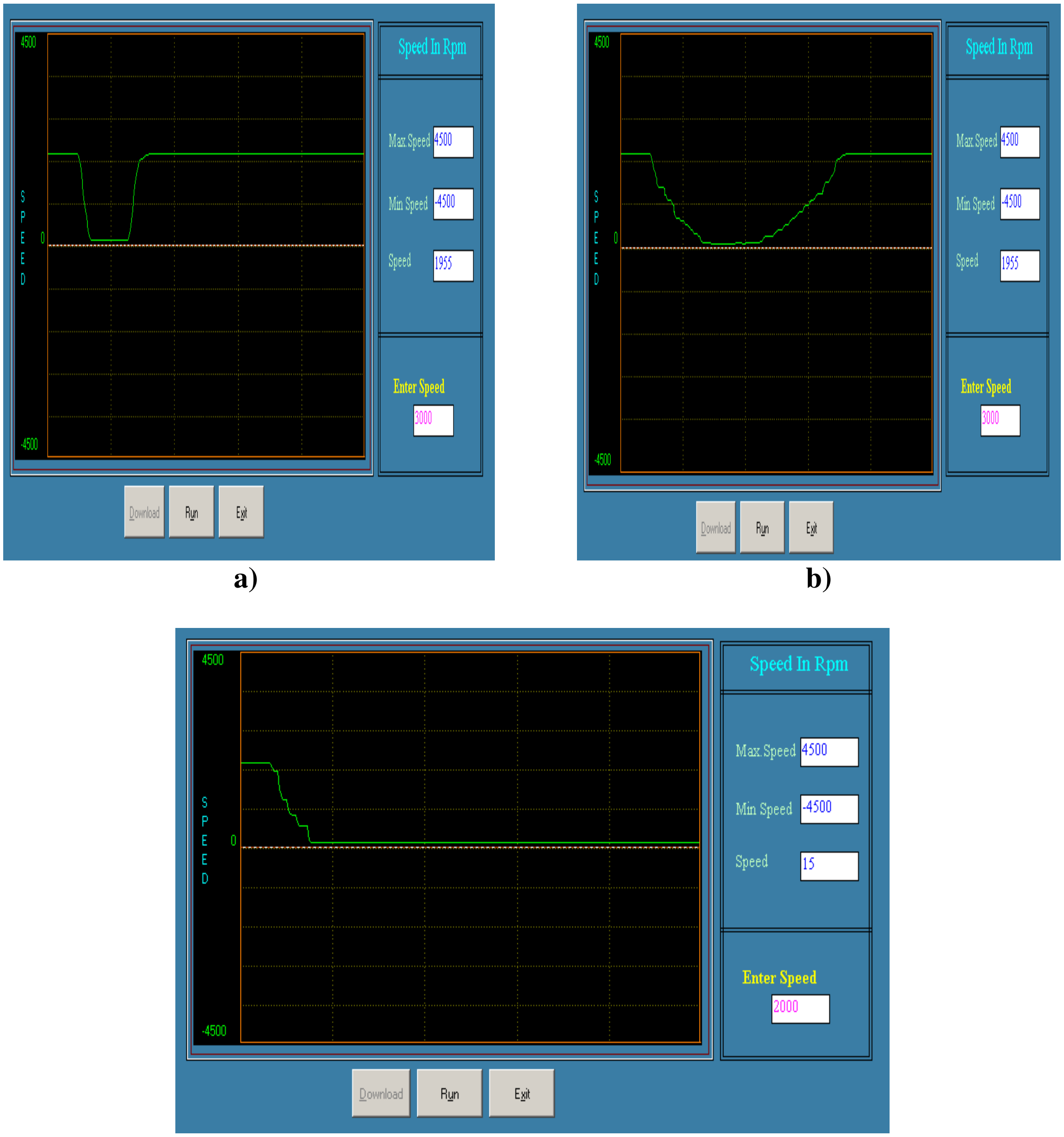
Max Speed 4500
Min Speed -4500
Speed 131
Enter Speed 1500

c)

Figure 8.8: Waveforms of different load conditions at a speed of 1500 rpm: a) At full load, b) Sudden increase in load, c) Linear Change in Load

8.6.5 CASE 4: At speed of 2000 rpm

When the load increases all of sudden at the speed of 2000 rpm, the motor draws more torque due to which a dip in speed is seen after this when the load is released the motor tries to stable at its synchronous speed.



Max Speed 4500
Min Speed -4500
Speed 1955
Enter Speed 3000

a)

Max Speed 4500
Min Speed -4500
Speed 1955
Enter Speed 3000

b)

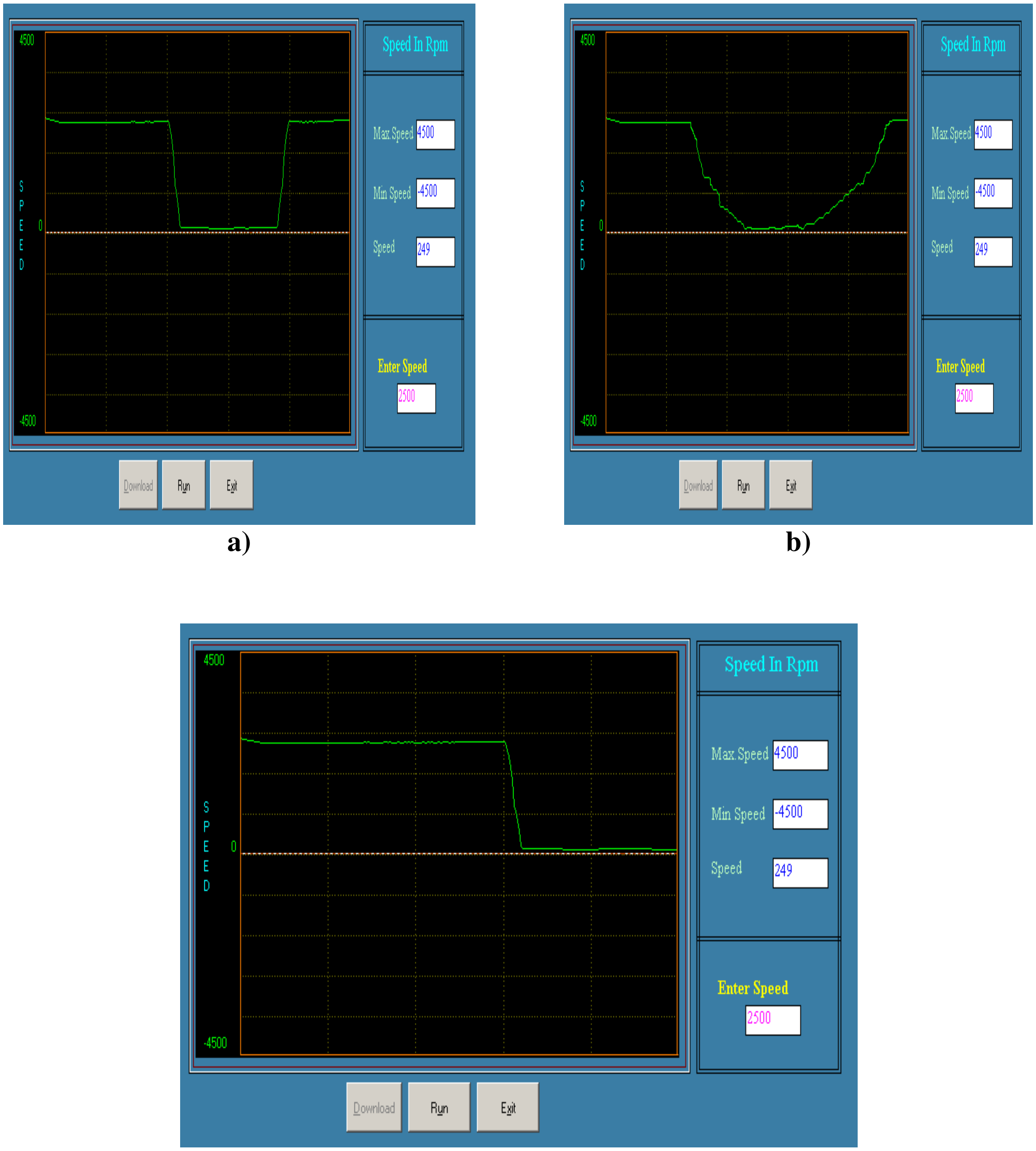
Max Speed 4500
Min Speed -4500
Speed 15
Enter Speed 2000

c)

Figure 8.9: Waveforms of different load conditions at a speed of 2000 rpm: a) Sudden increase in load, b) Linear Change in Load, c) At full load

8.6.6 CASE 5: At speed of 2500 rpm

When the load increases all of sudden at the speed of 2500 rpm, the motor draws more torque due to which a dip in speed is seen after this when the load is released the motor tries to stable at its synchronous speed.



Max Speed 4500
Min Speed -4500
Speed 249
Enter Speed 2500

a)

Max Speed 4500
Min Speed -4500
Speed 249
Enter Speed 2500

b)

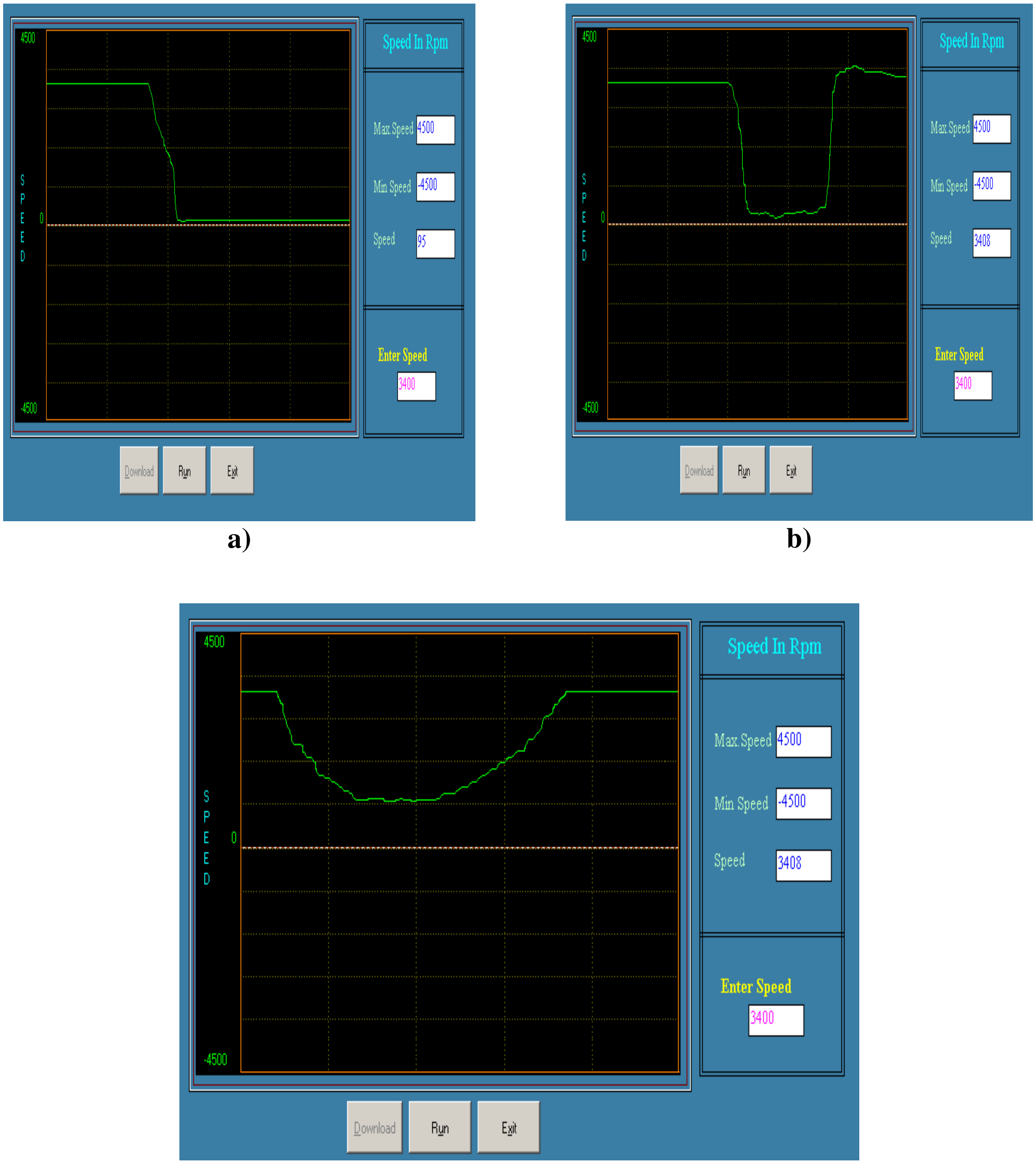
Max Speed 4500
Min Speed -4500
Speed 249
Enter Speed 2500

c)

Figure 8.10: Waveforms of different load conditions at a speed of 2500 rpm: a) Sudden increase in load, b) Linear Change in Load, c) At full load

8.6.7 CASE 6: At speed of 3400 rpm

When the load increases all of sudden at the speed of 3400 rpm, the motor draws more torque due to which a dip in speed is seen after this when the load is released the motor tries to stable at its synchronous speed.



a)

Max Speed 4500
Min Speed -4500
Speed 95
Enter Speed 3400

b)

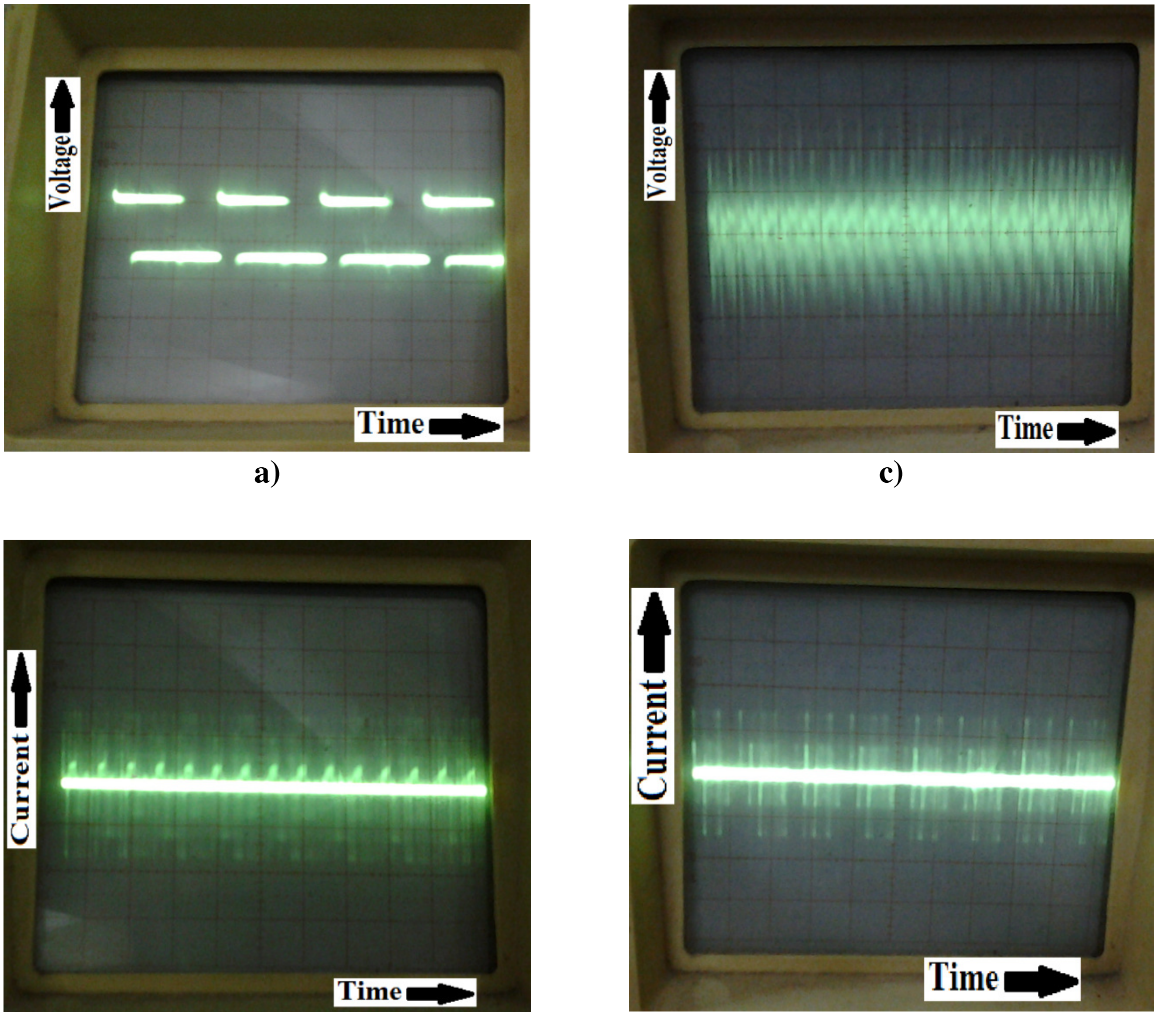
Max Speed 4500
Min Speed -4500
Speed 3408
Enter Speed 3400

c)

Max Speed 4500
Min Speed -4500
Speed 3408
Enter Speed 3400

Figure 8.11: Waveforms of different load conditions at a speed of 3400 rpm: a) At full load, b) Sudden increase in load, c) Linear Change in Load

8.6.8 EXPERIMENTAL WAVEFORMS OF IPM (Intelligent Power Module)



a) c)

b) d)

Figure 8.12: Waveforms of Intelligent Power Module: a) PWM signals b) I_{dc} current c) V_{dc} current d) I_1, I_2, I_3, currents.

8.7 CLOSURE

This chapter presents the experimental performance investigations of speed control scheme of IPM based PMSM on different load conditions. The speed control of PMSM motor using MICRO – 2407 (TMS320F2407) and IPM (PEC16DSMO1) is implemented. The performances and results are analyzed and discussed. Also a comparison of simulation and experimental results is made and analyzed.

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

CONCLUSIONS

Field-oriented control of a permanent magnet synchronous motor is designed, simulated and implemented in this work. SIMULINK is capable of showing real time results with reduced simulation time and debugging. Following conclusions are arrived:

1] The whole drive system is simulated by the use of MATLAB/SIMULINK. With the motor equations, a model for the machine has been developed in SIMULINK. The results of the simulation show the good response of the model when tracking a command speed.

2] 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.

3] Experimentation was conducted on PMSM drive in the laboratory and the results so obtained revels good response.

4] The simulation results and experimental result are similar thus validate the SIMULINK model of vector control of PMSM in MATLAB.

FUTURE WORK

Future works needed to be carried out to improve the performance of the motor.

1] A vector-controlled PMSM drive with a continually on-line learning Hybrid Neural-Network model-following speed controller is one of the advancement in vector control of PMSM in which the speed controller produces rapid, robust performance and accurate response to the reference model regardless of load disturbances or PMSM parameter variations.

2] The other is vector control of permanent magnet synchronous motor with surface magnet using artificial neural networks; the use of ANN makes the drive system robust, accurate and insensitive to parameter variations.

3] The speed is estimated by the measurement of the position. The speed estimation can be improved by the use of Kalman filters.

4] 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.

CHAPTER 9

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APPENDIX

Full specification of MIRO- 2407 (TMS320F2407A)

TMS320F2407A BASED DSP CONTROLLER

- Processor: TMS320F2407A
- Operating Speed: 40MHz
- 32KB on chip flash memory
- 16KB RAM for program memory
- 32KB RAM for Data Memory
- Opto Isolated RS232 serial port at 9 pin ‘D’
- 16x2 LCD interface
- 2 Limit switches provided for General purpose usage in the software. (Factory configured as Increment, Decrement switches)
- 34 pin Motor Control I/F Connector
    - 12 Motor Control PWM
    - 6 capture I/P signals
    - 2 Quadrature Encoder Interface
- 26 pin ADC I/F connector
    - 16 channel 10 bit ADC
    - 500ns conversion time / 2MSPS sampling speed
- 2 channel 12 bit DAC terminated at J801 connector

- **IPM (Intelligent Power Module)**

IPM BASED POWER MODULE (3hp) [PEC16DSMO-1]

- Power Module is designed for Motor control application up to 3 HP by using 3rd generation IGBT and DIODE technology based IPM.
- Input: 1Phase / 3 phase 50 Hz AC.
- Output: 400/10A (MAX), AC/DC on each leg of 3 phase bridge.

IPM (Intelligent Power Module)

- 1200V, 25A, 3 Phase IGBT Inverter Bridge.
- 1200V, 10A IGBT for over voltage braking.
- Built - in over voltage, under voltage, over current and over temperature protection.

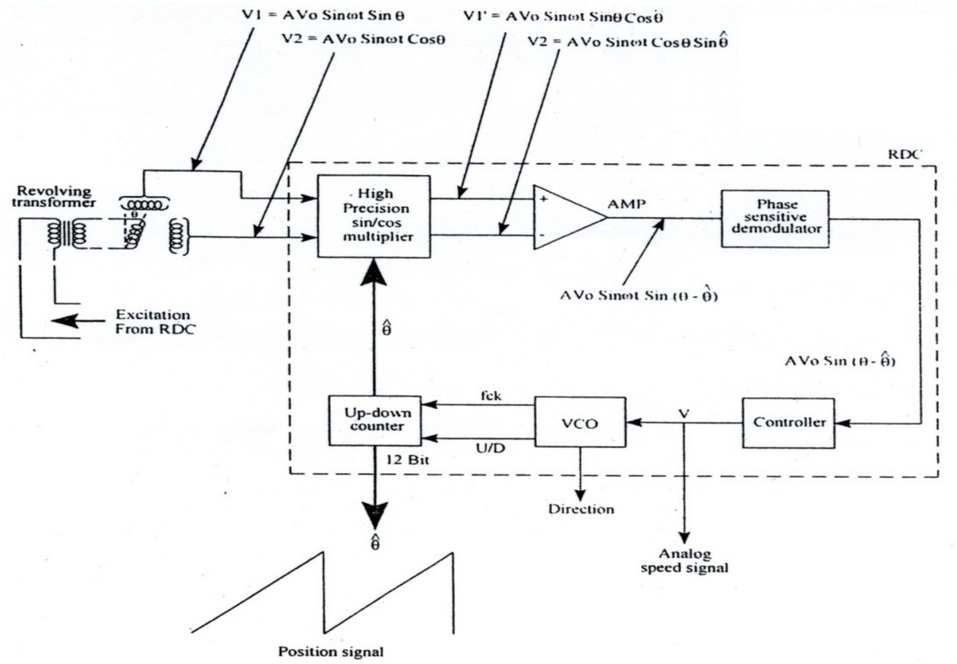
Additional Features

- 1200V, 25A Converter Bridge for AC-DC power conversion.
- 4 Nos of Hall Effect current sensors to sense the DC link current and 3 output current of the Inverter Bridge.
- 1 No of Hall Effect Voltage sensor to sense DC Link voltage.

- All the PWM signals are isolated using Opto Isolator.
- Protection circuit for over current with LED indication.
- Optically Isolated fault signal from the IPM is given to the Embedded/DSP controllers for Protection.
- Independent Power supplies for all isolated circuits.
- 0-900V Voltmeter to Indicate the DC Link Voltage.
- All current, PWMS and Feedbacks are terminated at Front panel.
- FRC Connectors are provided to Interface with the Embedded/DSP controllers.
- All the Input/output Lines are terminated at Banana sockets.

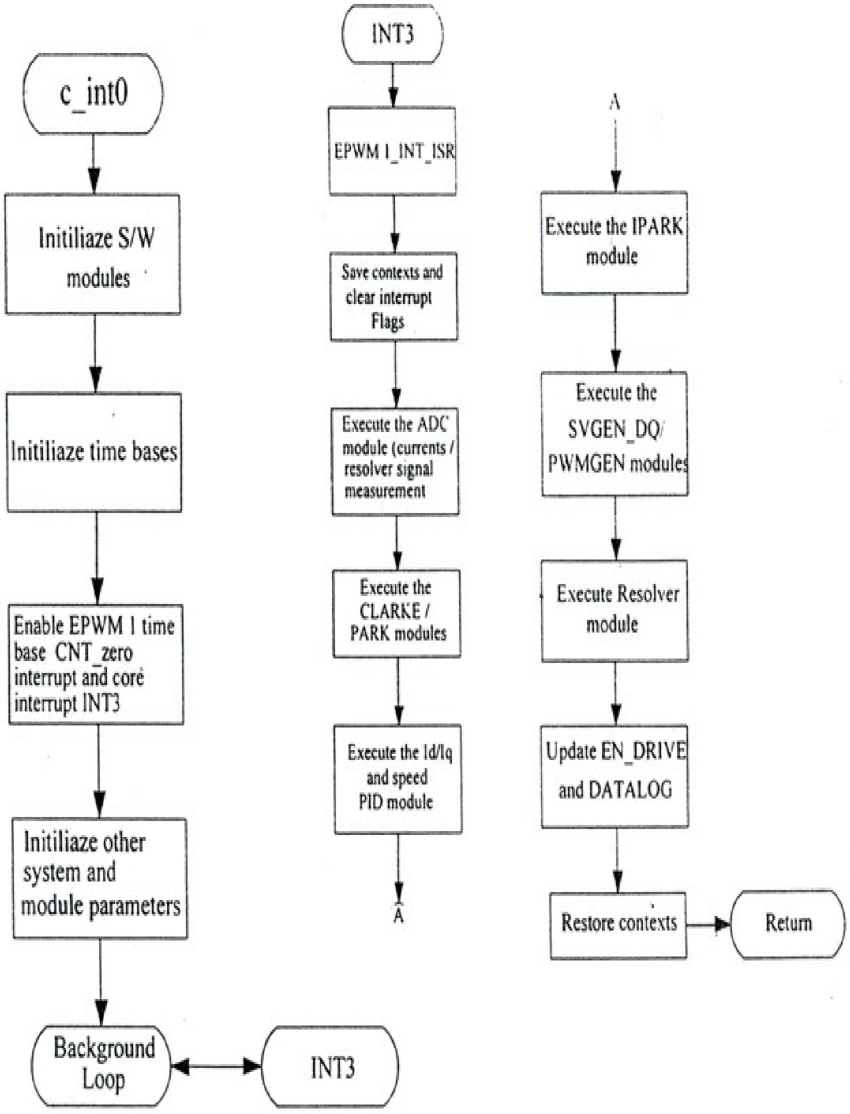
RESOLVER DESCRIPTION

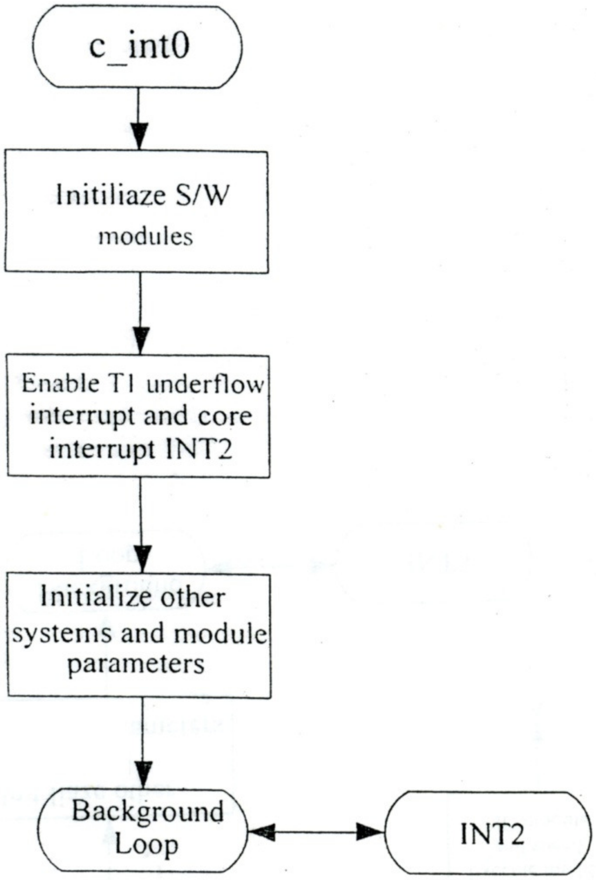
If, for example, θ = 0°, the horizontal stator winding will be decoupled, where as the vertical winding will give maximum voltage output because of maximum coupling. The analog output signals can be used directly or they can be processed through on RDC to obtain the digital signal. The RDC can be considered as a close loop position tracking servo system. It consists of a number of components indicated in the figure.

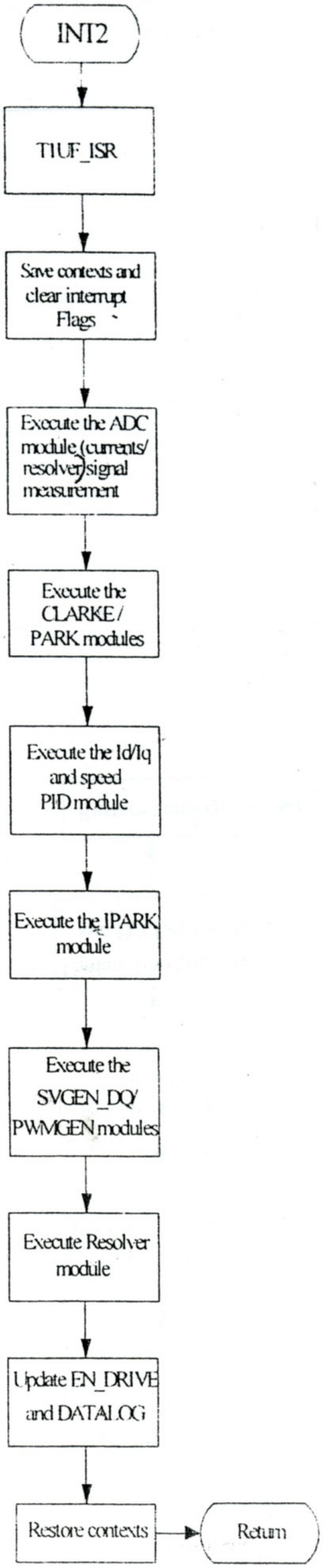


Additionally, it generates the carrier signal for the resolver. The high – precision sin/cos multiplier multiplies the input signals by cos θ and sin θ respectively, by the feedback estimated position signal $\hat{\theta}$ generated by up/down counter. Output signals V'_1 and V'_2 are subtracted from one another through an error amplifier to generate the $AV_0\sin \omega t. (\theta - \hat{\theta})$ signal of the output. A phase sensitive demodulator converts the signal to $AV_0\sin \omega t. (\theta - \hat{\theta})$ at its output. This signal is processed by an integral type controller. VCO and up down counter to generate estimate signal at the output. The tracking error will be 0 at steady because of integration in the controller and it will give the correct position signal at the counter output.

FLOW CHARTS




c_int0
Initiliaze S/W modules
Enable T1 underflow interrupt and core interrupt INT2
Initialize other systems and module parameters
Background Loop
INT2


INT2
T1UF_ISR
Save contexts and clear interrupt Flags
Execute the ADC module (currents/ resolver) signal measurement
Execute the CLARKE / PARK modules
Execute the Id/Iq and speed PID module
Execute the IPARK module
Execute the SVGEN_DQ/ PWMGEN modules
Execute Resolver module
Update EN_DRIVE and DATALOG
Restore contexts
Return