CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The development of high energy Permanent Magnet (PM) material makes the electric motors with PM excitation popular in servo applications. Among the PM motors, Interior Permanent Magnet Synchronous Motor (IPMSM) can offer many attractive characteristics in providing better efficiency, power density, wider speed range, saliency and torque to inertia ratio. The IPMSM is mainly a type of salient pole synchronous motor, which is a family of brushless AC machines. Members of this family have a standard three-phase stator winding with an inserted magnet in the rotor. The stator winding produces a spatial sinusoidally rotating magnetic field. Therefore, the IPMSM is also called salient pole permanent magnet synchronous motor.

Most of the early works reported in the 1970’s and 1980’s are related to line start PM machines where, the magnets are buried under the rotor with sufficient space for cage bars. The presence of cage bar provides good starting torque and also dampens the transient oscillations. This type of construction is called cage-rotor or line start IPMSM. In such machines, improved efficiency is achieved when compared to an induction motor.

With the development of power transistor technology and vector control theory in the late 1980’s, the performance of inverter fed IPMSM
drive has been improved drastically, which eliminates the need for cage winding. The inverter fed IPMSM drive has many advantages over any other AC machine. Some of the features are summarized as follows:

1. Improved saliency makes the IPMSM competitive with an induction motor, particularly in terms of power factor and inverter KVA requirement.
2. The efficiency can be improved by adding appropriate amount of magnet into the rotor core without making any change in stator design.
3. The control strategy of IPMSM is much simpler when compared to induction motor.

A detailed review on performance of IPMSM is presented in the following section

1.2 LITERATURE REVIEW

IPMSM drives are widely used for high performance applications such as robots, machine tools and hybrid vehicle. Simple cage-rotor IPMSM with v/f control are used for line start applications such as fans, blowers, air conditioners and centrifugal pumps. The stator of any IPMSM should resemble that of induction motor and many rotor configurations are being used to achieve high performance. The theory of dynamic equations for modeling, analysis and simulation of vector controlled motor drives is well discussed in the literature.
1.2.1 Mathematical Model of IPMSM

The basic dynamic equations for IPMSM model in phase (abc) coordinates can be derived from the salient pole synchronous machine with the equations for damper and field windings removed. Honsinger (1982) and Slemon (1990) presented a theoretical basis for deriving the motor equations from the machine equivalent circuit. Gorman et al (1988) suggested a simple experimental test to measure the electrical parameters, namely, stator inductances and magnetic flux linkages of poly-phase motors. However, these techniques are developed, based on the assumption that the stator windings and air gap flux density are distributed sinusoidally. Boldea (2006), El-Refaie et al (2006), Ishikawa et al (2005), Tomy et al (1989) and Kenjo (1985) have discussed modeling and analysis of permanent magnet synchronous machines in phase domain. This model is capable of predicting the machine parameters and back emf waveforms with spatial harmonics. An extension of this model is used for evaluating average torque, cogging torque and ripple torque (Colamartino et al 1999).

The modified winding function theory has become popular for modeling the synchronous machine under dynamic eccentricity. Jawad et al (2002) and Tabatabaei et al (2004) presented the modified winding function theory for non-uniform air gap in rotating electric machinery. Tu et al (2007) derived a simulation model to evaluate the parameters of the large synchronous generators under stator winding inter turn fault condition. In this research work, the IPMSM phase model is developed on the basis of modified winding function theory that takes into account all the space harmonics. Moreover, determination of machine inductance using machine geometry is presented.
Even though the phase coordinate model is feasible for simulation, simple two axis (dq) model is more useful for parameter identification and control purpose. As it is well known, the transformation of machine variables from the abc frame into the dq frame forces the sinusoidally time varying variables to become constant. Many works have been done on the dq modeling and high level torque control of IPMSM, as reported in Bose (2006), Krishnan (2005), Krause (2004), Pillay et al (1988) and Sebastian et al (1980).

1.2.2 Classification of Torque Control Strategy

The torque control can be classified as either linear torque control or non-linear torque control. The linear torque control is straightforward, which is proportional to q axis stator current. On the other hand, to take the advantage of the reluctance torque, many non-linear control strategies with various objectives are reported in the literature such as Unity Power Factor Control (Morimoto et al 1994), Constant Flux Linkage Control (Monajemy et al 1999 and Chandana et al 2003), Maximum Torque per Ampere Control (Schiferi et al 1990, Mongkol et al 2006, Ching-Tsai et al 2005, Macminn et al 1991 and Damien et al 1997), Maximum Torque per Flux Control (Jawad et al 2003) and Maximum Efficiency Control (Mademlis et al 2004 and Naomitsu et al 2003).

As far as fast transient response is considered, Maximum Torque per Ampere (MTPA) and Maximum Torque per Flux (MTPF) techniques are more attractive than any other non-linear control technique.

In MTPA control strategy, Ching-Tsai et al (2005) and Jahns et al (1986) stated that for achieving maximum torque, the stator current has to be optimized (i.e., copper loss is minimized) over the entire base speed.
While implementing MTPA control, the reference current has been derived as a function of torque, which involves the solution of a fourth order polynomial equation about the operating point. Moreover, the coefficients of polynomial equation are dependent on machine parameters.

In the case of MTPF using DTC strategy, Zhong et al (1997) and Ghassemi et al (2005) stated that the maximum torque control is achieved by regulating stator flux vector via applied voltage. While implementing the MTPF control, Rahman et al (1998) presented a varying flux command as a function of reference torque in stationary reference frame. However, the reference flux is dependent on the parameter. Jawad et al (2003) have suggested a parameter estimation method based on DTC of IPMSM drive.

The hysteresis comparator-based Direct Torque Control (DTC) technique is simple to implement, as it works with a limited number of voltage vectors available per sector. However, reduction in torque ripple and current distortion and achievement of fast torque dynamics are the most challenging requirements of DTC technique. Vas (1998) and Grahame and Lipo (2003), suggested that the choice on number of voltage vectors per sector has a direct influence on increasing current distortion and torque ripple. Kyo-Beum et al (2001) and Casadei et al (2000) suggested that the application of multilevel cascaded inverter with variable switching frequency eliminates torque ripple. However, the increase in number of voltage level results in increased cost and complexity of associated inverter circuit. Tang et al (2002 and 2003) have presented an alternative simple solution, which is to apply Space Vector Modulation (SVM) technique for DTC implementation. A modified DTC using SVM technique is developed in this research work, which simultaneously provides MTPF control.
In general, implementation of MTPA/MTPF control for a given torque requires online solution of reference signal, which is parameter-dependent. Sebastian (1995) finds that the stator resistance and rotor magnet flux vary with temperature. Ching-Tsai et al (2005) have presented the effect of stator resistance variation on PM motor. The effects of magnetic field saturation on PM motors are presented by Morimoto et al (1994). Shin (1998) has designed a suitable anti windup PI controller for accounting the saturation effects. The d and q axes inductances are known for their dependency on their air gap flux. Such variations in machine parameters during various operating conditions introduce an error in the generated reference signal, which in turn affects the controller performance. Thus, development of methods for parameter independent reference command generation simplifies the computational complexity in online. With this in mind, a new normalization technique is developed in this research for reference current/flux generation about each of the operating point of a given torque. Practical implementation of MTPA/MTPF control requires system parameter. A method for parameter estimation in offline has been presented by Lee (2006), Kim et al (2002) and Yasser et al (2006). Luuko et al (2003) have suggested a method for stator flux estimation for DTC of IPMSM drive.

### 1.2.3 Construction of Prototype Machine

Numerous design and construction aspects of IPMSM have been reported in the literature. Miller (1984), Hendershot et al (1994), Herslof (1996), Soulard et al (2000) and Tsuda et al (2007) have designed a large power rating machine with required volume of magnet and size of cage bars. Kazumi et al (2004) presented a simple design for low power cage-rotor IPMSM using NdFeB Magnet, which has the maximum energy product of 300kJ/m³ with limited temperature of 240°C.
With respect to construction of IPMSM, the cage-rotor IPMSM construction is simple, robust and is inexpensive. When the rotor has complex geometry, accurate prediction of machine parameters is required to obtain the desired closed loop performance. A detailed literature review on the existing modeling technique follows.

Conventional techniques like Finite Element Method and dq theory are being widely used to determine the machine parameters. Ho et al (2000), Jabbar et al (2003), and Kazumi et al (2004), presented a time stepping finite element analysis method for cage-rotor IPMSM. It is well known that the time stepping finite element analysis offers detailed field calculations in regions where the machine has complex shapes. Finite element methods are computationally intensive and require more time for simulation. Bianchi (2005), Wijenayake (1997) and Silvester et al (1996) presented an alternative approach to extract machine parameters from the finite element and use them in dq model as lumped parameters.

Rahman et al (1990), Rahman et al (1984), Miller (1989), Chee-Mun et al (1998) and Chaudhari et al (1998) developed a conventional dq model, which is widely used for performance analysis of the IPMSM. Such an approach is computationally fast but it does not represent space harmonics or asymmetries in the motor. Therefore, an effective modeling technique is required to combine the speed of the conventional dq model and the flexibility of FEM for studying the performance of cage-rotor IPMSM.

Circuit (MEC) (Vlado 1986, Moallem et al 1998). The main advantage of this model is that it is possible to predict transient and steady state performance of any machine with any type of winding distribution and air gap length. In this research work, reluctance-mmf network based machine model is developed for cage-rotor IPMSM, which includes stator and rotor teeth reluctances. In addition, the same model can be extended further to any other AC machines with necessary modifications in the reluctance-mmf network. The reluctance-mmf network based model is very much useful in predetermination of maximum loading capacity and sizing of power converter.

1.2.4 Parameter Estimation of IPMSM

Several methods have been reported to estimate the parameter of IPMSM. A model based online estimation algorithm has been proposed to estimate stator inductance in Kim et al (2002). However, the estimation accuracy is influenced by inaccuracies in the stator resistance and magnets flux linkage. The application of the adaptive estimation schemes such as extended kalman filter for estimation of machines has been reported in Yasser et al (2006). These estimation algorithms have utilized Recursive Least Square (RLS) method, which involves iterative procedure for the estimation of parameters and their convergence to real values. Iterative procedures are computationally complex. Jovanovic et al (1997) presented a model for estimating the motor parameters offline, which is also computationally intensive. Lee (2006) presented parameter estimation by minimizing the state estimation error using an iterative gradient algorithm. The most common problem of these estimators is their dependence on accurate measurement and knowledge of the model. Niazi et al (2007) have proposed a simple method for online estimation of PM-assisted synchronous reluctance motor parameter making use of multiple reference frames. The same concept is extended further to IPMSM drive in this research work. Naziruddin et al (2002) have
suggested the flow chart for real time implementation of MTPA control system.

1.2.5 Simultaneous Torque and Rotor Power Extraction

Xiaogang et al (2000) proposed a new field-rotor IPMSM and its working principle. It has both PM poles and excitation poles on rotor and retains the conventional three phase stator winding. The permanent magnets provide constant air gap flux and the excitation poles act as the flux regulator to adjust the air gap flux distribution.

Masoud et al (2005) have demonstrated that in the absence of excitation in a Salient Pole Synchronous Machine (SPSM), its stator flux could be augmented with any arbitrary frequency to transmit electric power across air gap, while still producing the mechanical torque. This provides contactless power transmission to the rotor mounted electronic equipments viz., rotational antenna, turret systems and magnetic amplifiers, which eliminate slip rings. This can be achieved through pulse width modulation with current error tracking controller. However, the amount of torque production in SPSM is limited due to its saliency when compared to a field-rotor IPMSM. In this research work, performance analysis of the IPMSM is carried out in both cage-rotor and field-rotor form. A proposal of parameter independent reference signal generation is investigated on the information gathered from the literature.

1.3 OBJECTIVE OF THE THESIS

The main objective of this thesis is to develop an efficient torque control algorithm for IPMSM drive and validate it through simulation and
experimentation. The following specific objectives are formulated for achieving the required performance in IPMSM.

1. To develop parameter-independent reference current/flux generation for MTPA/MTPF control of the given IPMSM drive.
2. To develop a reluctance-mmf network-based model of IPMSM and apply it to a prototype cage-rotor IPMSM.
3. To validate the effectiveness of the proposed control strategy on the prototype machine, including online parameter estimation.
4. To extend the proposed control strategy to field-rotor IPMSM where simultaneous rotor power extraction is also possible.

1.4 ORGANIZATION OF THESIS

The research work reported in this thesis is organized into seven chapters. Chapter 1 provides a comprehensive literature survey and the objectives of the study.

Chapter 2 introduces the development on IPMSM performance analysis and enhancement reported in the literature. Based on the geometrical information of machine, evaluation of stator inductances using modified winding function theory is introduced. The open circuit magnet flux linkages are calculated from air gap flux density. The dq models are built for parameter estimation and control purposes. A short survey on parameter variations and its impact on different torque control strategy are also presented.
Chapter 3 provides the necessary conditions for achieving maximum electromagnetic torque in the IPMSM drive. Based on this condition, the actual torque is significantly simplified into normalized basis. The control algorithm for implementing MTPA/MTPF scheme is discussed. The simulation result of the proposed MTPA/MTPF scheme is compared with existing schemes.

Chapter 4 gives the background information on modeling, simulation and control of cage-rotor IPMSM. Effects and improvement of cage-rotor IPMSM with reluctance-mmf network is discussed through simulation studies. An attempt is made to develop a reluctance-mmf network based model for various electrical machines. Experimental results are presented to validate the developed methodology.

Chapter 5 proposes a laboratory experimental setup for practical MTPA control scheme along with a simple parameter estimator. The simulation and experimental results are shown to highlight the effectiveness of the proposed MTPA control.

Chapter 6 extends the idea of MTPF scheme for simultaneous torque control and rotor power delivery on field-rotor IPMSM. The simulation results are validated through experimental setup.

Chapter 7 summarizes the major contributions of this research work. This chapter also includes a brief note on the possible directions for further research work.