CHAPTER 1
INTRODUCTION

1.1 Motivation

Due to the merits of being able to achieve higher efficiency, higher power density, higher torque to inertia ratio, wide speed range, and free from maintenance, the interior permanent magnet synchronous motors (IPMSMs) are now receiving growing research interests in many industrial drive applications. For example, here are some application fields like air conditioner drives [1, 2], hybrid and fuel cell vehicle drives [3], electric vehicle drives [4], traction and machine tool spindle drives [5], and integrated starters/alternators [6, 7]. Especially, while the permanent magnets are buried inside the rotor core, the resulting PMSM, called interior permanent magnet synchronous motor, has a mechanically robust rotor structure that is very suitable for high speed operation. Moreover, due to the difference between the d-axis and the q-axis inductances, the IPMSM contains an extra torque component, namely the reluctance torque, as compared with that of a surface mounted PMSM.

Although there are many vector control methods in the existing literature for variable speed applications of IPMSMs, basically, they can be classified as either linear torque control strategy or nonlinear torque control strategy. For example, by letting the d-axis stator current (i_{ds}) be equal to zero such that the q-axis current (i_{qs}) is proportional to the torque command, it is quite straightforward to achieve a linear torque control [e.g. 8-10] to achieve high performance. However, the potential reluctance torque of the IPMSM is not fully expolited. On the other hand, to take advantage of the reluctance torque, many nonlinear torque control strategies such as unity power factor control [11], constant flux linkage control [11], maximum torque per ampere (MTPA) control [12-16], maximum efficiency control [17, 18] were developed to achieve different objectives. The unity power factor control method keeps the phase voltage and the phase current of the IPMSM to be in phase. The constant stator flux linkage control method maintains the magnitude of the stator flux linkage be equal to that of the permanent magnet flux linkage. To obtain a given torque, both of these two previous control methods need smaller voltages than that of the MTPA control method. However, the MTPA control can obtain a minimum copper loss as well as can achieve a maximum output torque capability for an IPMSM as the core loss model is ignored. The maximum efficiency control method considers a core loss model in the IPMSM model. The corresponding combined equations of the copper loss and the core loss are then minimized. For the above mentioned nonlinear controls, the corresponding q-axis current command was first generated by the demanded torque and the corresponding i_{ds} was then decided according to the specific objective. However, this renders the design of the resulting controller more difficult. In view of the above problems, it is the major motivation of this dissertation to propose a linear torque control strategy for an IPMSM drive to fully exploit its potential torque capability to achieve high performances and meanwhile simplify the corresponding controller design.

1.2 Literature Survey

Due to the availability of Neodymium Iron Boron (NdFeB), the permanent magnet synchronous motors (PMSMs) have been widely used in industrial drive applications to achieve high performances. In addition, the interior permanent magnet synchronous motors (IPMSMs), having a robust rotor structure and capable of operating over wide speed range, are gaining increasing popularity in recent years. The power capability and field weakening performance of an IPMSM had been extensively studied [e.g. 19-22]. It had been concluded that the IPMSM can offer higher output power and wider field weakening speed range as compared with that of the surface mounted PMSM [21, 22]. These promising characteristics are attracting research interests for further study. For example, some focused on the study of machine-parameter measurements including saturation effects to obtain more accurate model of an IPMSM [e.g. 23-34]. The saturation effects on the parameters of an IPMSM under variable load conditions were investigated according to the current phase angle [26, 29]. The cross saturation effect on the machine model had been presented and shown by some experimental results [23, 25, 28]. In [31-34], the studies were focused on the lumped parameter model for an IPMSM corresponding to the d- and q-axis currents . For example, E. C. Lovelace et al. [33] presented a lumped-parameter model for an IPMSM accounting for the effects of saturation to estimate the q-axis inductance. The corresponding d-axis inductance was kept constant by assuming that the d-axis magnetic path was largely unsaturated except at the structural rotor bridges where it was fully saturated at full load. Recently, B. Stumberger et al. [34] presented an extensive study of the evaluation of saturation and cross-magnetization effects in an IPMSM over the entire range of the d- and q-axis excitations respectively. The conventional two-axis IPMSM model is modified to include the influence of anisotropy, saturation, and cross-coupling effects on the variation of self- and cross-coupling inductances in the d- and q-axis. This modified model is satisfactory. It offers a better analysis of the saturation and cross-coupling effects in an IPMSM. However, the application of the modified model in an IPMSM drive to improve the performance is still an expectation. Some other efforts were focused on the design of the rotor structure to achieve a larger constant power speed range (CPSR) [e.g. 35-37]. As described in [35], an axially-laminated IPMSM was designed and the corresponding CPSR was demonstrated to be 7.5:1 which showed an extremely wide CPSR. The magnetic saturation effects in the motor magnetic paths are receiving more attentions than the temperature effect on the residual flux density and intrinsic coercivity in the permanent magnet. But the temperature effect also influences the performance of a PMSM drive [38, 39]. As described in [38], in the normal range of operating temperature, as the temperature is increased, the residual flux density and intrinsic coercivity of the permanent magnet will decrease. Hence, to obtain constant torque from a PMSM over a wide temperature range, temperature compensation may be needed to adjust the current. Also in [39], R. Krishnan et al. proposed a parameter compensation scheme using reactive power feedback control, such that this reactive power can be used to compensate for the variation in torque caused by the variation of permanent magnet flux linkage.

From the application point of view, the torque control strategy of an IPMSM is essential for a high performance motor drive system. The torque control strategies of IPMSM drives can be commonly classified as the direct torque control [e.g. 40-48] and the two-axis vector control [e.g. 8-18 and 49-55]. For the direct torque control (DTC) scheme, M. F. Rahman et al. first applied the direct torque control (DTC) scheme that was widely used in the induction motor drives to IPMSM drives [40]. The basic principle of DTC is to directly select stator voltage vectors according to the differences between the references of torque and stator flux linkage and their actual values. The DTC scheme can achieve fast torque response by changing the rotating speed of the stator flux linkage as fast as possible. In [48], a comparative analysis for field weakening operation in vector controlled and DTC IPMSM drives was presented. It was concluded that the vector control scheme was more stable at higher speed (field weakening) operation region and the corresponding torque ripple was smaller than these of DTC scheme. On the other hand, the DTC scheme had a simple algorithm that did not require any high-precision position transducer if reliable flux estimation was performed. And the DTC scheme also resulted in faster torque response. For the vector control scheme, extensive studies had been presented. For example, they were i_{ds}=0 control [8-11], unity power factor control [11], constant flux linkage control [11], maximum torque per ampere (MTPA) control [12-16], maximum efficiency control [17, 18], field weakening control [49-55]. Except for the i_{ds}=0 control, most vector control strategies generate the q-axis current command according to the desired torque, then the corresponding d-axis current command is calculated according to the corresponding specific objective. It renders the generated torque nonlinear to the d- and q-axis currents.

Another popular research direction is for the sensorless control of IPMSM drives [e.g. 56-63]. Due to the consideration of reducing the hardware cost and enhancing the structural robustness for high performance motor drives, the position sensorless control is desirable. For example, Z. Chen et al. [58] first proposed an extended EMF for the mathematical model in the stationary reference frame which included both rotor position information from the EMF and the stator inductance such that sensorless control for SPMSMs can be extended to IPMSMs. S. Morimoto [61] presented another extended EMF model in the rotating reference frame to estimate both position and speed. The research interests focused on different sensorless control techniques are still continuing.

1.3 Contributions of the Dissertation

This dissertation focuses on proposing a linear torque control strategy to fully exploit the potential reluctance torque as well as to simplify the outer loop controller design over the entire operational speed range for IPMSM drives. The theoretical basis of the proposed control strategy is derived and analytical derivations are given for references. For the proposed vector control strategy, during the transient response, the maximum available torque is used to achieve fast dynamic performance. In addition, under the steady state operation, one attempts to minimize the copper loss of an IPMSM drive. Since the rotor structure of an IPMSM exhibits a salient pole characteristic, the d- and q-axis inductances are not the same. Under heavy load condition, the q-axis flux linkage tends to saturate. Thus, a new flux linkage model is proposed to consider this saturation effect and the corresponding linear torque control strategy is rederived. The major contributions of the dissertation can be summarized as follows:

Firstly, a novel linear torque control strategy is presented for IPMSM drives in the constant torque limit region such that the resulting torque is proportional to the line current magnitude. A sufficient condition for the existence of the linear torque control is derived and the corresponding torque constant is also maximized. In addition, a closed form relation between the i_{ds} and i_{qs} for the proposed torque control strategy is also derived. It turns out that the proposed linear torque control strategy can not only fully exploit the reluctance torque to provide a much wider constant torque operation region but also can provide a much better performance at higher speed region as compared with that of the surface mounted PMSM.

Secondly, a new field weakening control of a linear torque controlled IPMSM drive is presented. The proposed control further extends the operational speed range of the previous LTC from the constant torque limit range to the field weakening range such that the IPMSM drive can operate over much wider speed range. The theoretical basis of the proposed field weakening control is first proposed and the corresponding analytical forms are also derived. The whole operational regions of an IPMSM are divided into three regions according to the motor speed. They are the constant torque limit region (Region I), the partial field weakening region (Region II), and the full field weakening region (Region III). However, only two control modes, namely the constant torque limit control mode and the field weakening control mode, are required. A region detector is proposed to choose the correct control mode efficiently according to the motor speed and the demanded torque. In addition, to fully use the maximum torque capability in the field weakening region, a variable line current magnitude limiter is also proposed to simplify the complexity of the control algorithm.

Thirdly, a linear maximum torque per ampere (LMTPA) control is proposed for interior permanent magnet synchronous motor drives to further minimize the copper loss during the steady state operation as well as to achieve fast transient response. The proposed LTC is also extended to the entire field weakening region to achieve full range maximum torque per ampere control. Sound theoretical basis is also provided in the context.

Fourthly, a new saturated q-axis flux linkage model for an IPMSM is proposed and the corresponding LMTPA control strategy over the full operational speed range is re-derived. Some comparative experiment results are provided to show the improvement of the transient as well as the steady state performances for the proposed saturated-LMTPA control strategy.

1.4 Outline of the Contents

The contents of this dissertation can be outlined as follows:

In Chapter 2, a novel linear torque control strategy is proposed for IPMSM drives such that the resulting torque is proportional to the line current magnitude. A sufficient condition for the existence of the linear torque control is also derived and the corresponding torque constant is also maximized. In addition, a closed form relation between i_{ds} and i_{qs} is also derived. Finally, a prototype drive system is also implemented by using a DSP TMS320F240 and some experimental results are presented to verify the feasibility of the proposed linear torque control strategy.

In Chapter 3, extension of the proposed LTC in Chapter 2 from the constant torque limit range to the field weakening range is presented. Firstly, the theoretical basis of the proposed field weakening control is presented and the corresponding analytical forms are also derived. Then, the whole operational regions of an IPMSM are divided into three regions according to the motor speed. They are the constant torque limit region (Region I), the partial field weakening region (Region II), and the full field weakening region (Region III). Furthermore, a region detector is proposed to choose the correct control mode efficiently according to the motor speed and the demanded torque. In addition, to fully use the maximum torque capability in the field weakening region, a variable line current magnitude limiter is also proposed to simplify the complexity of the control algorithm. Finally, the proposed control is also implemented fully digitally by using a fixed point DSP TMS320F240 to simplify the hardware circuits and some experimental results are given to verify the effectiveness of the proposed linear torque control strategy over the field weakening region.

In Chapter 4, A linear torque control strategy extending the existing maximum torque per ampere control in the constant torque limit region up to the entire field weakening region is proposed. The theoretical basis of the proposed LMTPA control is firstly presented.

Extension of the proposed control to the field weakening region is then discussed. The proof of the proposed control to achieve maximum torque per ampere (i.e. minimum copper loss) over full speed range is also given. For easy implementation, an adaptive limiter is also adopted for efficiently implementing the proposed control strategy over the entire speed range. Finally, a prototype is also constructed by using a fixed point DSP TMS320F240 and some experimental results are given to verify the validity of the proposed control strategy.

In Chapter 5, a new saturated model for the q-axis flux linkage is proposed. The corresponding LMTPA control strategy is then derived. The control algorithms to achieve the proposed control are presented. For simplifying hardware circuit, the control programs are implemented fully digitally by using a fixed point DSP TMS320F240 and some comparative experimental results are provided to show the merits of the proposed control strategy.

Finally, conclusions are made and some future research topics are given in the last chapter.