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INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVES

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ABSTRACT

Lately, Interior Permanent Magnet Synchronous Motor (IPMSM) has been widely engaged in many industrial applications due to its high performance and high efficiency. They are robust high power-density machines adapted to be operating at high motor and inverter efficiency over wide speed ranges, including extensive ranges of stable-power operation. Unlike Permanent Magnet Synchronous Motor (PMSM), Interior Permanent Magnet Synchronous Motor (IPMSM) possess special characteristic over extended speed range by the flux weakening operation since the Permanent Magnet Synchronous Motor (PMSM) flux cannot be weakened directly. Control of the IPMSM at rated speed and below is achieved by use of the Maximum Torque per Ampere (MTPA) mode of operation utilizing a series approximated approach. Control above base speed is achieved based on an approximation of the flux-weakening (FW) mode of operation. A closed loop control system with a Proportional Integral (PI) controller in the speed loop has been imply to operate in Maximum Torque per Ampere (MTPA) and Flux-Weakening (FW) regions. This project uses Vector Control as the control strategies and the drive system based on Field Oriented Control (FOC) is developed, simulated and implemented. The entire drive system is simulated in MATLAB/Simulink based on mathematical model of the system devices including dynamic model of Interior Permanent Magnet Synchronous Motor Drive (IPMSM) and inverter. The aim of the drive system is to have speed control over wide speed range.

ABSTRAK

Akhir-akhir ini, Interior Tetap Magnet Synchronous Motor (IPMSM) telah terlibat secara meluas dalam pelbagai aplikasi industri disebabkan oleh prestasi yang tinggi dan kecekapan yang tinggi. Mereka adalah mesin ketumpatan kuasa yang tinggi yang mantap disesuaikan untuk beroperasi pada motor yang tinggi dan kecekapan penyongsang julat kelajuan lebih luas, termasuk julat luas operasi yang stabil-kuasa. Tidak seperti Tetap Magnet Synchronous Motor (PMSM), Interior Tetap Magnet Synchronous Motor (IPMSM) mempunyai ciri-ciri khas pada julat kelajuan yang dilanjutkan oleh operasi yang semakin lemah fluks sejak (PMSM) fluks Magnet Tetap Synchronous Motor tidak boleh menjadi lemah secara langsung. Kawalan IPMSM pada kelajuan rated dan ke bawah dicapai dengan penggunaan Tork maksimum per Ampere (MTPA) Mod operasi menggunakan siri pendekatan hampir. Kawalan di atas kelajuan asas dicapai berdasarkan persamaan kepada fluks-lemah (FW) Mod operasi. Satu sistem kawalan sistem tertutup dengan Integral (PI) pengawal berkadar dalam gelung kelajuan telah membayangkan untuk beroperasi di Tork maksimum per Ampere (MTPA) dan Fluks-yang lemah (FW) wilayah. Projek ini menggunakan Kawalan Vektor sebagai strategi kawalan dan sistem pemacu berdasarkan Kawalan Berorientasikan Field (FOC) dibangunkan, simulasi dan dilaksanakan. Seluruh sistem pemanduan adalah simulasi dalam MATLAB / Simulink berdasarkan model matematik peranti sistem

termasuk model dinamik Dalam Negeri Tetap Magnet Synchronous Motor Drive (IPMSM) dan penyongsang. Tujuan sistem pemacu adalah untuk mempunyai kawalan kelajuan pada julat kelajuan lebar.

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LIST OF SYMBOLS

emf	-	electromagnetic force
L	-	per phase armature self-inductance
R	-	per phase armature resistance
pwm	-	pulse width molated
V_a, V_b, V_c	-	Terminal voltages of phase a, b, and c
i_a, i_b, i_c	-	Stator current of phase a, b, and c
e_a, e_b, e_c	-	Back emf of phase a, b, and c
ω_m	-	Mechanical rotor speed
K_e	-	Back emf constant
$f(\theta_e)$	-	Trapezoidal function
θ_e	-	Electrical angle of rotor
T_e	-	Electromagnetic torque
K_t	-	Torque constant
T_L	-	Load torque
J	-	Inertia of the rotor and coupled shaft
β	-	Friction factor
$V_c(t)$	-	Output of PI controller
K_p	-	Proportional gain

K_i	-	Integral gain
$e(t)$	-	Instantaneous error signal
UL, LL	-	The upper and lower limits
I*	-	Reference current

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CHAPTER 1

INTRODUCTION

1.1. Research Background

Interior permanent magnet synchronous motor IPMSM is getting more and more popular in applications like a traction and machine spindle drives, air conditioning compressors, electric vehicle, integrated starters/alternators. The reason why the IPMSM is getting more attentions is due to its attractive characteristic like high efficiency, high power density, high torque/inertia ratio, wide speed operation range and free from maintenance. This project describes the development of IPMSM drives using MATLAB/Simulink simulator.

The development of IPMSM drives requires the utilization of variable-frequency converter, which act as an interface between the utility power system and IPMSM. The converters can be classified based on rectifier and inverter used and it is called voltage source inverter (VSI). A PWM inverter controls both the frequency and the magnitude of the voltage output. Therefore, at the input, an uncontrolled diode bridge rectifier is generally used. One possible method of generating the inverter switch control signals is by comparing three sinusoidal control voltages with a triangular waveform at a selected switching frequency.

Vector control is a smart technique of the controlling IPMSM. Field oriented control is one of the commonly used for vector control. The vector control technique, employing a current controlled voltage source inverter (VSI), provides a method of variable speed control for the IPMSM that has fast responsive and follows command speeds accurately and precisely.

1.2. Problem Statement

The development of drive for interior permanent magnet synchronous motor is not a simple task. Unlike permanent magnet PMSM, IPMSM geometry has a mechanically robust rotor construction, a rotor saliency and low effective air gap. Constant power characteristics could be achieved over an extended speed range with the IPMSM by means of flux weakening since the PMSM cannot be weakened directly. Such extended-speed operating characteristic make the IPMSM a candidate for applications requiring constant power operation [1]. Furthermore, over excitation conditions in a PMSM drive pose potential dangers to the drive electronics when the magnet-generated motor back EMF significantly exceeds the source voltage at high speeds. The rotor saliency can be employed to reduce the permanent magnet excitation flux requirements in the IPSM in order to achieve extended-speed operating ranges while proportionally reducing the over excitation amplitude and its attendant risks. Rotor saliency provides opportunities for reducing the volume of magnet material in the IPMSM [2]. Additionally, IPMSM become the suitable choice in hybrid electric vehicles (HEV) compare to PMSM because its performance which is produce high power against weight ratio and much higher torque at low speed. Knowledge of principle drives in IPMSM is require in order to develop drives system for IPMSM.

1.3. Objectives

The objective of this project is to implement Field Oriented Control (FOC) that capable to operate within Maximum Torque per Ampere (MTPA) and Field-Weakening (FW) region of operation.

The goal of this project are to:

- Develop the modeling of the drive system for Interior Permanent Magnet Synchronous Machine (IPMSM).
- Implement an FOC method capable of maximum torque per ampere (MTPA) and flux-weakening (FW) in Matlab/Simulink.

1.4. Scope of Project

This project mainly focuses on:

- Modeling and simulating the Interior Permanent Magnet Synchronous Motor drive which is conducted in MATLAB/Simulink as software tools.
- Modeling drive system of the motor by choosing field oriented control (FOC) as control drive for Interior Permanent Magnet Synchronous Motor (IPMSM).
- Test the performance and dynamics of the IPMSM by switching the mode of operation either to choose under maximum torque per ampere (MTPA) or flux-weakening (FW) operation which is implemented in speed controller system.

1.5. Expected Outcomes

In the end of this project, the driver for IPMSM should be developed along with simulation result with the using of MATLAB/Simulink. Consequently, simulation results should meet the objectives of this project.

1.6. Report Outline

The contents of this report are organized as follows, Chapter 1 provides the research background, problem statement, objectives and scope of this project. Chapter 2 presents the reviewed literature on the permanent magnet synchronous motor and the analytical scheme of motor drives. The mathematical model of IPMSM and control drive of the AC machines explained in this chapter. Chapter 3 discusses an approach to find the possible designs that meet all the given performance specifications. Chapter 4 describes the constructed block diagram by using MATLAB/Simulink and preliminary result of the control scheme. Chapter 5 presents the conclusion and expected work to be completed.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Permanent Magnet Synchronous Motors (PMSM) are attracting growing attention for a wide variety of industrial applications, from simple applications like pumps or fans to high performance drive like a machine-tool servos. This is due to their main characteristic: high power density, high torque to inertia ratio and high efficiency.

In comparison with the conventional synchronous machines, where an electric winding also produces the rotor field, the PMSM has no wires in the rotor, which reduces the copper losses of the machine. Also due to the lack of rotor windings there is no need for brushes and slip rings. Taking all this into account, a PMSM machines has a smaller size and a higher efficiency, for a given power, compared to a conventional synchronous machines. On the other hand, the field produced by the permanent magnet is constant and cannot be controlled as easy as the conventional doubly electric excited machines, by changing the field current.

The PM machines can be classified as in the diagram in figure 2.1. First, depending on the nature of the stator field excitation, the PM machines can be classified as PM with D.C excitation (PMDC) or PM with A.C excitation (PMAC). The PMDC motor has the same configuration as the conventional DC machine, having a stator winding with brushes and comutator, except for the rotor, where the rotor (field) winding was replace with permanent magnets. The PMAC machine is a synchronous machine, with no brushes or comutator.

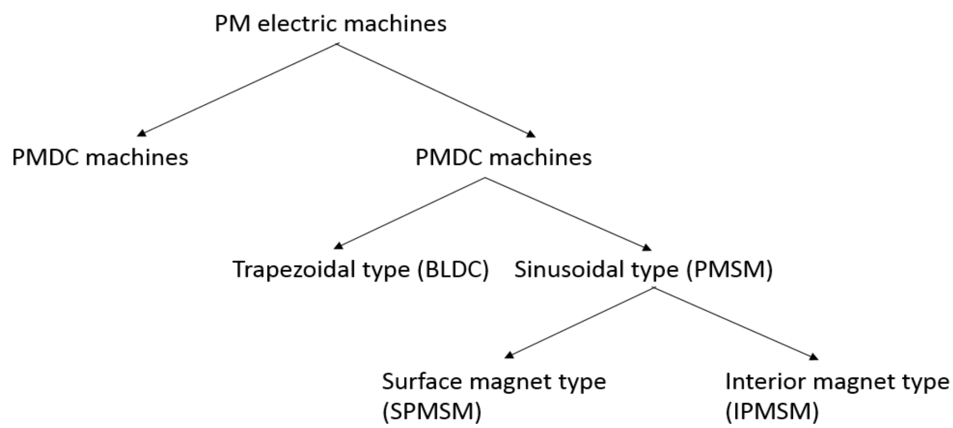

Figure 2.1: Permanent magnet machines classification.

Further, depending on the type of back-EMF voltage induced in the stator winding, the PMAC machines can be classified as trapezoidal-type PMAC machines or sinusoidal type PMAC machines. The trapezoidal PMAC machine, also called brushless DC machine (BLDCM), is excited form a rectangular current waveform, whereas the sinusoidal type requires AC stator excitation. The presence of torque ripples in a trapezoidal-type PMAC machine, and also due to development of vector control for AC drives encouraged the usage of sinusoidal PMAC, also known as PM synchronous machines (PMSM).

The PMSM can be classified into two types, depending on the positioning of the magnets in the rotor of the machine. These are the surface mounted PM machine (SMPMSM) and interior mounted PM machine (IPMSM), like presented in Figure 2.2.

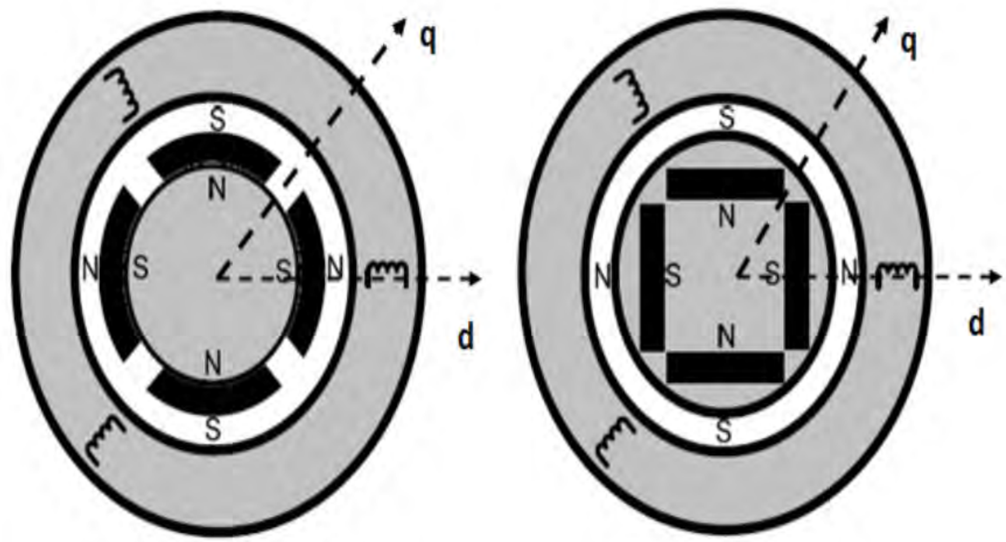

Figure 2.2: Cross section showing the difference between the SMPMSM and IPMSM.

For the SPMSM the magnets are placed on the surface of the rotor core Figure 2.2, while for the IPMSM the magnets are buried in the rotor core Figure 2.2. As shown in fig the magnetic flux induced by the magnets defines the rotor direct axis, d (magnetization axis) through the centerline of the magnets. The rotor quadrature, q axis is situated at 90 electrical degrees, from the d axis. For the interior PMSM the d axis air gap is increased compared to the q axis air gap, due to the fact that the relative permeability of the permanent magnet is close to 1, which is relative permeability of air. So, for the IPMSM the d axis reluctance is higher than the q axis reluctance. This means that the q axis inductance L_q is higher than the d axis inductance L_d. This brings saliency to this type of machine, where the saliency ratio is defined as:

$$\xi = \frac{L_q}{L_d}$$

2.2. Mathematical Equation of IPMSM

This subchapter present the development of mathematical model for torque control equation by using d-q axis model of the IPMSM, current vector control with Maximum Torque per Ampere (MTPA) and vector control. A mathematical model of the IPMSM is used in order to simulate the performance of the machine in Matlab.

2.2.1. Torque Control Equation Te for IPMSM

The steady-state analysis of a sinusoidal IPMSM machine with an equivalent circuit and phasor diagram continues the same as a wound field machine apart from that the equivalent field current I_f should be considered constant, that is the flux linkage $\Psi_f = L_m I_f = constant.$ the circuit equations can be written as [3]:

$$v_{qs} = R_s i_{qs} + \omega_e \acute{\psi}_{ds} + \omega_e \hat{\psi}_f + \frac{d}{dt}\psi_{qs} \quad (1.1)$$

$$v_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + \frac{d}{dt}\psi_{ds} \quad (1.2)$$

And the torque equation is

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{1.3}$$

The mathematical model of an IPMSM driver can be described by the following equations in a synchronously rotating rotor d-q reference frames as:

$$\psi_{ds} = \hat{\psi}_f + L_{ds} i_{ds} \tag{1.4}$$

$$\psi_{qs} = L_{qs} i_{qs} \tag{1.5}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left[\hat{\psi}_f i_{qs} + \left(L_{ds} - L_{qs}\right) i_{ds} i_{qs}\right] \tag{1.6}$$

The equivalent circuit representation of the voltage equations, in the dq reference frame is presented in Figure 2.3.

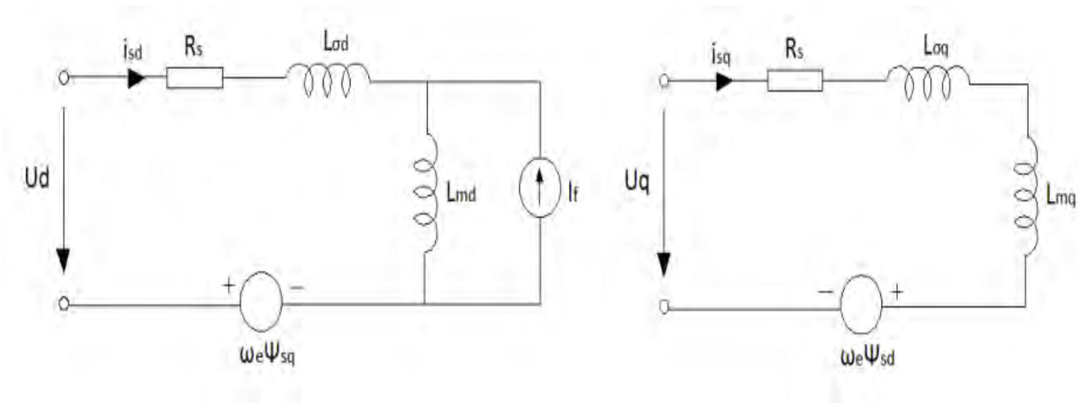

Figure 2.3: Equivalent circuit representative of *dq* voltage equation for IPMSM.

2.2.2. Current Vector Control with Maximum Torque/Ampere

To derive maximum/torque criteria, it is better to normalize the torque expression and express it as function of normalized stator current components. D-axis current i_d is maintained at zero. Defining the base torque as:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\hat{\psi}_f I_B \tag{1.7}$$

Where the base current I_B is defined as:

$$I_B = \frac{\hat{\psi}_f}{L_{qs} - L_{ds}} = I_f \frac{L_{dm}}{L_{qs} - L_{ds}} \tag{1.8}$$