Control of Permanent Magnet Synchronous Motor using MRAS

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Abstract-

The permanent magnet synchronous motor is increasingly playing an important role in advanced motor drives. An encoder or resolver attached to the shaft of the motor typically supplies the feedbacks required for motor speed control. Many advanced motor drives cannot tolerate the use of these feedback devices because of reliability concerns in a harsh environment, price, space and weight limitations. In this paper model reference adaptive system-based adaptive strategy has been used for speed estimation. In compare to previously developed methods in the literature such as: EKF, neural networks and sliding mode control this method consumes less computational time and it is easy to implement and this method MRAS is completely independent of stator resistance (Rs) and is less parameter sensitive, as the estimation algorithm is only dependent on q-axis stator inductance (Lq). In this proposed method the Popov's criterion is used for adaptive speed estimation. The validity of the proposed adaptive strategy has been verified by simulation and experiments.

Keywords – Model reference adaptive system(MRAS) Permanent magnet synchronous motor(PMSM),Field oriented control(FOC)

I. INTRODUCTION

Permanent Magnet Synchronous Motor (PMSM) is a rotating electrical machine that has the stator phase windings and rotor permanent magnets. Three-phase stator windings produce a rotating magnetic field through the three-phase AC. Rotor is equipped with high-performance permanent magnet in surface or inside of ferromagnetic materials such as neodymium iron, boron or rare earth magnetic materials to obtain a strong magnetic field[1]. And the rotor magnetic field to distribute for the sine or look like a sine wave form. The air gap magnetic field is provided by these permanent magnets and hence it remains constant. The conventional DC motor commutates itself with the use of a mechanical commutator whereas PMSM needs electronic commutation for the direction control of current through the windings[2]. As the PMSM motors have the armature coils at the stator, they need to be commutated externally with the help of an external switching circuit and a three phase inverter topology is used for this purpose[3][4]. 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[5].

The torque is produced because of the interaction of the two magnetic fields which causes the motors to rotate. In permanent magnet motors, one of the magnetic fields is created by permanent magnets and the other is created by the stator coils[6][7]. The maximum torque is produced when the magnetic vector of the rotor is at 90 degrees to the magnetic vector of the stator. With the development of permanent magnetic materials and control technology, permanent magnet synchronous motor (PMSM) is mostly used due to high torque/inertia ratio, high power density, high efficiency, reliability and ease for maintenance, and is used in CNC machine tools, industrial robots and so on[8][9]. The establishment of the simulation model of PMSM and its control system is of great significance to the verification of a variety of control algorithms and the optimization of entire control system[10]. To achieve high performance, the vector control of the PMSM drive is employed.

The Space Vector Pulse Width Modulation (SVPWM) method is an advanced, computation-intensive PWM method and possibly the best among all the PWM techniques for variable frequency drive application [11] [12]. Because of its superior performance characteristics, it has been finding widespread application in recent years [13][14].
The PI (Proportional Integral) and PID (Proportional Integral Derivative) controllers are well-known and widely used in power system control applications as they are simple to realize, easily tuned and several rules were developed for tuning their parameters[15].

II. MATHEMATICAL MODEL OF PMSM

The following assumptions are made before establishing the mathematical model of PMSM:

• Neglects the saturation of the electric motor ferrite core.
• Neglects turbulent flow and hysteresis loss in electric motor.
• The current in electric motor is symmetrical three phase sinusoidal current.

2.1. d-q reference coordinate system

There are two kinds of coordinate system in FOC. One is fixed on the stator, which is a static coordinate system relative to us; the other is fixed on the rotor, which is a revolving coordinate system. Both the three-phase stator A-B-C coordinate system based on three-phase winding of three-phase stator and the two-phase stator α-β coordinate system are the static coordinate system. The two-phase stator α-β coordinate system is composed of α axis fixed on A axis and β axis that is vertical to α axis. While d-q coordinate system with d axis fixed on the rotor spool thread is revolving. Figure 1 shows the relationship of α-β coordinate system and d-q coordinate system.

![Figure 2.1 Relationship of α-β coordinate system and d-q coordinate system.](image)

The most common method in analyzing electric control PMSM is d-q axis mathematical model, which can be used in analyzing the stable state performance of PMSM as well as in studying the transient state performance. The mathematical model of PMSM is usually composed of the voltage equation, the stator flux linkage equation, the electromagnetism torque equation, the mechanical movement equation. The equations under d-q coordinate system can be expressed as follows:

The stator voltage equations are

\[ V_d = R_s I_d + \frac{p}{2} \omega L_m I_q + \omega L_d I_q \]
\[ V_q = R_s I_q + p \lambda q + \omega \lambda \]

Flux linkages in the coils are

\[ \lambda_q = L_q I_q + L_m I_q \]
\[ \lambda_d = L_d I_d + L_m I_r \]

Assuming

\[ I_d^2 = I_f, I_q^2 = \Omega \]
Equation becomes
\[ \lambda_q = L_q I_q \]

Substituting this in voltage equation
\[
\begin{align*}
V_d &= R_s I_q + p \lambda_q + \omega L_d I_d + \omega L_m I_f \\
V_q &= -R_s I_d + p \lambda_d - \omega L_m I_q
\end{align*}
\]

Electromagnetic torque equation is
\[ T_e = p(I_q \lambda_d - I_d \lambda_q) \]

Mechanical movement equation is
\[ \frac{J d\omega}{dt} = T_e - T_f \]

III. SPEED CONTROL THEORY

In DC motors, the flux and torque producing currents are orthogonal and can be controlled independently. The magneto motive forces, developed by these currents are also held orthogonal. In AC machines, the stator and rotor fields are not orthogonal to each other. The only current that can be controlled is the stator current. Field Oriented Control is the technique used to achieve the decoupled control of torque and flux by transforming the stator current quantities (phase currents) from stationary reference frame to torque and flux producing currents components in rotating reference frame.

3.1. Space vector pulse width modulation technique

In motor theory, motor speed is defined by the formula
\[ N = \frac{60f}{p} \]
where f-Power frequency and p-pole pair
Through the formula , speed regulate need change the power frequency or the motor pole pairs, and change power frequency easier than change motor pole pairs, so, at present, the great mass of motor speed regulate use frequency convert. Currently, use the type of: AC-DC-AC. It’s means, convert 3-phase power AC into DC, then, invert the DC into 3-phase AC and change frequency.

3.2. DC-AC converter

The inverter switches available today are thyristors, bipolar junction transistors (BJTs), MOS field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs) and gate turn off thyristors (GTOs). 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 applications in the low and medium power range. The power devices when used in motor drives applications require an inductive motor current path provided by antiparallel diodes when the switch is turned off.

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.

It has six power switches a,b,c,a',b',c' which are grouped into S(a,b,c) and S(a',b',c'). It means each voltage vector is coded by three digit number and have eight possible switching states. Consider the state S(1,0,0).

The point [a], [b'], [c'] switch ON, and [a], [b],[c] switch OFF. So, \( U_{an}=U_{dc} \) and \( U_{bn}=U_{cn}=0 \). Substitute this values in (3.1)

\[
U_a = \sqrt{2} U \cos(\omega t - \frac{\pi}{3})
\]

\[
U_b = \sqrt{2} U \cos(\omega t - \frac{2\pi}{3})
\]

\[
U_c = \sqrt{2} U \cos(\omega t - 4\pi / 3)
\]

Similarly voltages for all the eight switching states are calculated.

3.3 Model Reference Adaptive System (MRAS)

A block diagram of the proposed MRAS based PMSM rotor speed estimator is shown in Fig.3.2. The reference model calculates instantaneous reactive power (Qref) and the adjustable model computes steady-state reactive power (Qest). The instantaneous and steady state reactive power are compared to form the error signal. The error signal is then passed through an adaptation mechanism to estimate the rotor speed. The estimated rotor speed based on the computation is used to tune the adaptable model until the two reactive powers (Qref and Qest) become identical. The proposed Model reference adaptive System, continuous monitoring of speed error signal and reactive power error signal is required otherwise positive feed-back may take place and the system may become unstable.

The stability of such closed loop estimator is achieved through Popov’s Hyperstability criterion. The method is simple and requires less computation. Depending on the quantity (i.e. the functional candidate) used to formulate the error signal; various kinds of MRAS are possible. In, an MRAS is developed with d and q-components of flux. However, the method is heavily dependent on stator resistance variation and suffers from the integrator related problems like drift and saturation. To overcome the problem, an MRAS with on-line stator resistance estimation, Reactive power-based MRAS and Neural Network (NN) based MRAS is used. Among all of these methods, reactive power based MRAS is more popular for speed estimation as it is independent of stator Reference model utilizes instantaneous reactive power and the Adjustable model uses steadystate reactive power. This means that the two different versions of the same quantity are used to formulate error signal. This type of approach rewards a speed estimator that depends only on ‘Lq’. A mechanism for on-line estimation of ‘Lq’.

Fig 3.2 Block diagram of MRAS

\[
\begin{align*}
\text{Reference Model} & \quad \text{Adjustable Model} \\
V_{d*} & \quad \text{Adaptation Mechanism} \\
V_{q*} & \quad \omega_{r} \\
I_{d*} & \quad I_{q*} \\
Q_{d*} & \quad Q_{q*}
\end{align*}
\]
3.4. FOC based Speed Control

The basic principle of FOC is to make the permanent magnetic flux vector and the stator current vector be aligned with the perpendicular d- and q-axis respectively in order to produce the maximum electro-magnetic torque. It is achieved by setting the d-axis current to zero and conventional PI control scheme is usually adopted to regulate the d-axis current. FOC control is actually control of phase and amplitude for a motor stator voltage or current vector at the same time. The motor torque will depend on the stator current space vector $\mathbf{i}_s = i_d + j i_q$. When the permanent magnet flux and the direct excitation, cross-axis inductance is confirmed. In other words, control $i_d$ and $i_q$ that can control the motor torque. Current $i_d$ as excitation current, on the id of the control, in practical application there are three kinds of general circumstances, this paper use $i_d = 0$ of the control strategy.

In this control system, stator current $i_A$, $i_B$ outputted by the inverter is measured using electric current sensor, and $i_C$ is calculated with the formula $i_C = -(i_A + i_B)$. Transform the electric current $i_A$, $i_B$, $i_C$ into the direct component $i_q$, $i_d$ in the revolving coordinate system through the Clarke and the Park transform. Then $i_q$, $i_d$ can be used as the negative feedback quantity of the electric current loop. The deviation between the given speed and the feedback speed $n$ is regulated through the speed PI regulator. The output is $q$ axis reference component $i_{qref}$ to control the torque. The deviations between $i_{qref}$, $i_{dref}$ and current feedback quantity $i_q$, $i_d$ go through the electric current PI regulator, and the respectively output phase voltage $V_{sqref}$ and $V_{sdref}$ on the d-q revolving coordinate system.

IV SIMULATION AND RESULTS

4.1. Simulink model of FOC based PMSM

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Figure 4.1 shows the simulink model of FOC based speed control in PMSM. The system includes one PI controller for the speed loop and two PI controllers for the inner current loop, $dq/afβ$ block, SVPWM, VSI block with IGBT and a PMSM model. The selected PI values of the outer speed loop are $P=0.01$ and $I=4$. The PI parameters of inner current loop are $P=4$ and $I=0.11$. The controllers are tuned according to trial and error method. The direct voltage bus is 300v. The switching frequency is taken as 10 KHz and a PWM carrier frequency is of 5 KHz. Simulation is carried out for 0.1 sec. The PMSM control system mainly includes: PMSM power module, coordinate transformation module and SVPWM production module.

Figure 4.2 Speed response (rpm)

![Speed response (rpm)](image)

Figure 4.2 shows the speed response of the PMSM drive with proposed SVPWM. Machine is accelerated from standstill to 530 rpm.

Figure 4.3 Electromagnetic torque (Nm)

![Electromagnetic torque (Nm)](image)

Figure 4.3 shows the electromagnetic torque developed in the machine when a load torque of 1Nm is applied at 0.05s.

V. CONCLUSION

The whole drive system is simulated by the use of Matlab/Simulink. Starting with the motor equations, a model for the PMSM has been developed in Simulink, as well as models for the SVPWM signal generator, 2-level inverter, PI controller, Park transformations and MRAS. The results of the simulation show the good response of the model when tracking a command speed. The simulation results have proved that the proposed space vector pulse width modulation based control of a permanent magnet synchronous motor drive has a good performance for the torque, speed and position control of PMSM using MRAS. The results obtained shows that SVPWM control strategy based on MRAS approach can be applied successfully for PMSM drives with low cost.
REFERENCES


