Modelling and Simulation of Field Oriented Control of Permanent Magnet Synchronous Motor Drive

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Abstract- *Permanent magnet synchronous motor (PMSM) is widely used in high performance and high efficiency motor drives required for applications such as traction, robotics, machine tools, rolling mills, adjustable speed drives and electric vehicles. PMSM has replaced induction motors in various applications due to their high power density, high efficiency, high torque to inertia ratio and high reliability. This paper presents the design and implementation of field oriented control of PMSM drive. Out of the several methods of speed control such as pole changing, frequency variation, variable stator voltage, constant V/f control, slip recovery method, vector control etc., Vector control method has been employed in PMSM drive to obtain better dynamic response. The detailed mathematical modelling of vector control for PMSM drive is done in MATLAB Simulink environment.*

Keywords- PMSM, Vector control, MATLAB / Simulink.

I. INTRODUCTION

Electric drives play an important role in every industry. Drive system are classified as constant-speed drives and adjustable speed drives. Generally, A.C machines which operate with fixed frequency sinusoidal supply are used for constant-speed drives and the D.C machines for variable-speed drives. However, DC motors have disadvantages of maintenance issues due to presence of commutators and brushes, losses due to sparking, high rotor inertia and higher costs. Therefore, in few decades DC motors have been replaced by AC motors in various applications in which PMSM has gained an increasing interest in recent years. PMSM is preferred over induction motors because of its advantages such as high power density, high efficiency, high torque to inertia ratio and high reliability and controllability.

PMSM has the configuration similar to that of traditional synchronous machines with the absence of slip rings and field winding. PMSMs are not only operated in constant torque region when the speed is below base speed but also in constant power region over a wide speed range. The rotor construction of PMSM is same as that of BLDC motors which has permanent magnets that creates constant magnetic field and the stator structure resembles that of induction motor, where the windings are placed in such a way as to produce sinusoidal flux density in the airgap of the machine. The use of magnets empowers an effective utilization of the radial space and replaces the rotor windings, subsequently reducing the rotor copper losses. There are two types of PMSM depending on the mounting of permanent magnets. One is surface mounted PMSM and another is interior mounted PMSM which is the most widely used type of PMSM.

II. MATHAMETICAL MODELLING AND ANALYSIS

Consider a two-poled three phase Permanent Magnet Synchronous Motor. The d-q model is expressed in rotor reference frame as follows,

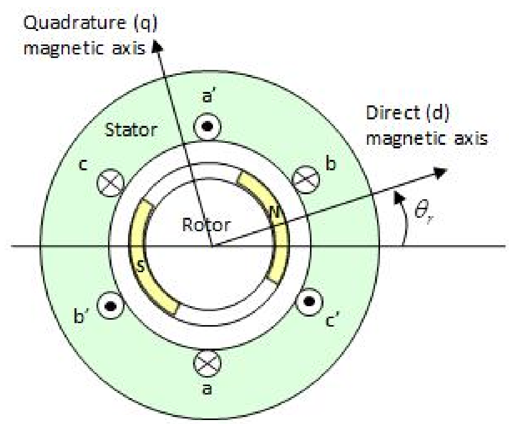

Figure 1. Rotor reference frame

$$\frac{di_d}{dt} = -\frac{r_s}{L_d} i_d + \omega_e \frac{L_q}{L_d} i_q + \frac{v_d}{L_d} \quad (1)$$

$$\frac{di_q}{dt} = -\omega_e \frac{L_d}{L_q} i_d - \frac{r_s}{L_q} i_q + \frac{v_q}{L_q} - \omega_e \frac{\lambda_m}{L_q} \quad (2)$$

By rearranging the terms in equation (1) & (2), we can obtain the voltage equations as

$$v_d = r_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (3)$$

$$v_q = r_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_m \quad (4)$$

The torque developed in the motor is given as,

$$T_e = \frac{3}{2} P \{\lambda_m i_q + (L_d - L_q)(i_d i_q)\} \quad (5)$$

$$\omega_e = \frac{P}{2J} \int (T_e - T_L - \frac{2B\omega_e}{P})\, dt \quad (6)$$

Where,

L_d, L_q are the d and q axis inductance in Henry (H).

v_d, v_q are the d and q axis voltages in volts (V).

i_d, i_q are the d and q axis currents in ampere (A).

r_s is the stator resistance in ohms (Ω).

ω_e is the rotor electrical speed in rad/sec.

λ_m is the permanent magnet flux linkage in V/rad/sec.

J is the moment of inertia in Kgm^2.

B is the vicious friction gain in Nm/rad/sec

P is number of poles.

T_L is the load torque in Nm^2.

T_e is the electromagnetic torque in Nm.

III. FIELD ORIENTED CONTROL

The most common control strategies for brushless motors are trapezoidal control, sinusoidal control and field oriented control. Among which FOC method is employed for the drive system as it achieves smooth and efficient operation with fast dynamic response at both low and high speeds. Independent control of torque and speed can be accomplished by using FOC, where two currents responsible for torque and field are separately resolved and controlled (q-axis current and d-axis current).

In Field oriented control, motor currents and voltages are controlled in d-q reference frame of the rotor. This implies that the measured motor currents are transformed from the three-phase stationary reference frame (a, b, c) of the stator windings to two axis rotating d-q reference frame. Also, the voltages to be supplied to the motor are transformed from d-q frame of the rotor to the three phase reference frame of stator before they can be utilized to generate the voltage control signals for the inverter that is fed to motor.

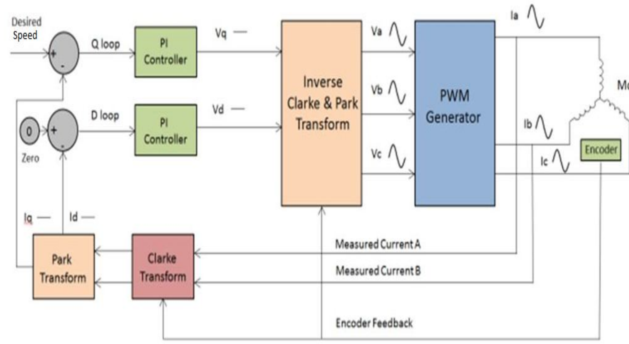

Figure 2. Block diagram of FOC

The coordinate transformation includes Park transformation, Clarke transformation and their inverse.

A. Clarke transformation-

Clarke transformation converts balanced three-phase stationary quantities into balanced two-phase stationary quantities (a, b, c $\rightarrow$ α, β).

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (7)$$

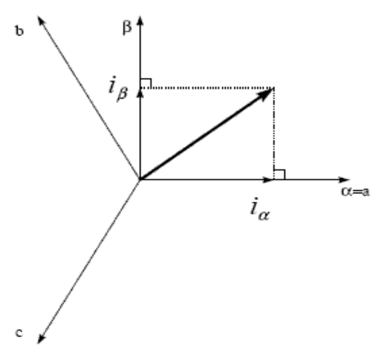

Figure 3. Clarke transformation

B. Park transformation-

Park transformation converts two-axis orthogonal stationary reference frame quantities into rotating reference frame quantities ($\alpha, \beta \rightarrow d, q$).

$$\begin{bmatrix} x_{ds} \\ x_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (8)$$

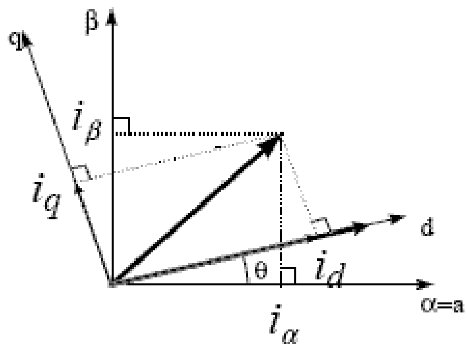

Figure 4. Park transformation

C. Inverse Clarke transformation-

Inverse Clarke transformation converts a two-axis stationary reference frame quantities to a three-phase stationary reference frame ($\alpha, \beta \rightarrow a, b, c$).

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \qquad (9)$$

D. Inverse Park transformation

Inverse Park transformation converts the rotating reference frame quantities into two-axis stationary reference frame quantities ($d, q \rightarrow \alpha, \beta$).

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} x_{ds} \\ x_{qs} \end{bmatrix} \qquad (10)$$

IV. SIMULINK IMPLEMENTATION

The PMSM drive system discussed above is modelled in simulink as shown in figure 5. The PMSM control system consists of several independent functional modules: PMSM module, coordinate transformation module, SPWM generation module, inverter module and PI controller module.

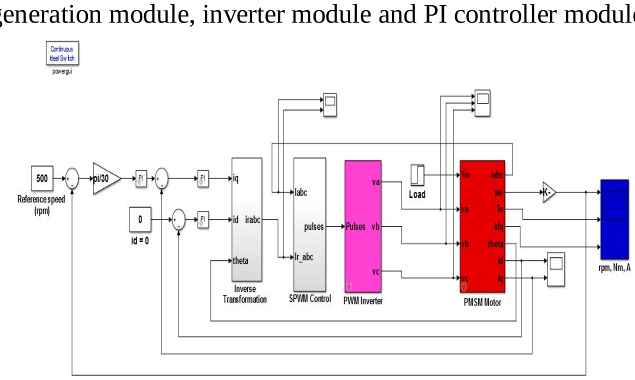

Figure 5. Simulink model of PMSM drive using FOC technique

The model includes inner current loop and outer speed loop. The inner current loop has two PI controller for both d and q axis current separately. The outer speed loop is provided with PI speed controller. The drive system consists of motor model, the inverter which is fed by 200V dc supply. The pulses to the three-phase mosfet bridge inverter are provided by SPWM block. The inverter drives the motor to generate controlled rotor speed. To check the model performance and field oriented control, simulation is carried out for various load cases. Here, the simulation is run for two cases, one where the motor is started on a load which is maintained constant throughout the operation and another where the load is applied to the motor after some time elapse.

Case 1: The reference speed is set to 500rpm with the load of 5Nm from the start. The phase current waveform observed is as shown in figure 6.

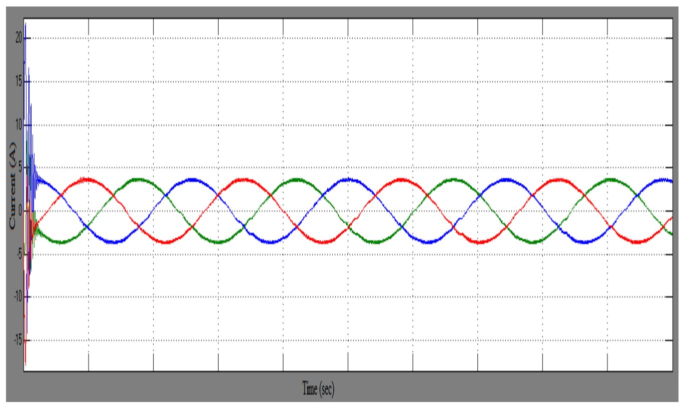

Figure 6. Phase Current waveforms of Case 1

The speed, torque, direct axis and quadrature axis waveforms are shown in the figure 7.

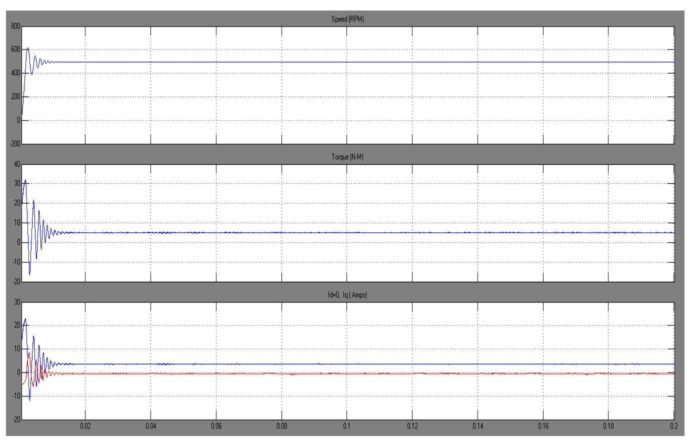

Figure 7. Speed, Torque and Current waveforms of Case 1

Case 2: The reference speed is set to 500rpm and a load of 5Nm is applied to motor at 0.2secs. The phase current waveforms are shown in figure 8.

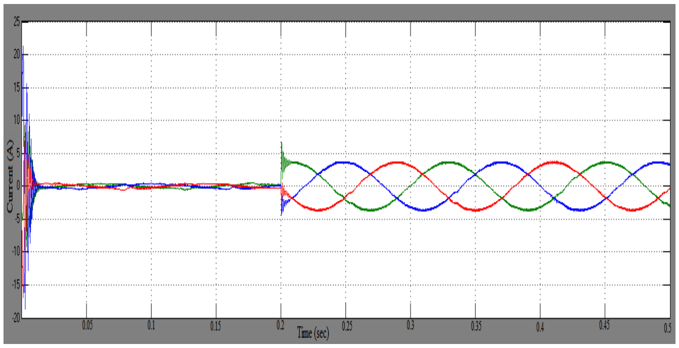

Figure 8. Phase Current waveforms of Case 2

The speed, torque, direct axis and quadrature axis waveforms are shown in the figure 9.

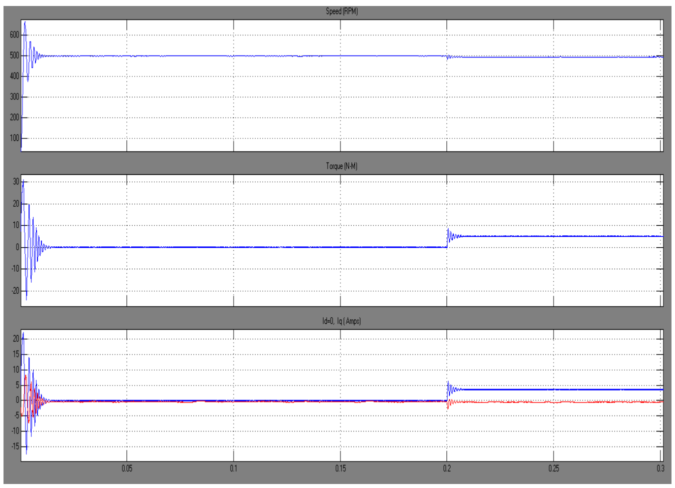

Figure 9. Speed, Torque and Current waveforms of Case 2

As per figure 9, it can be observed that at time t=0.2 secs a load torque of 5Nm is applied with corresponding change in phase currents. Below table gives the details of motor control and input parameters. Based on these parameters, speed response, torque and currents are observed.

Table 1.

Parameters	Value
Pole pairs P	3
Stator Resistance Rs	1.4 Ω
Inductances Ld=Lq	0.0066 H
Inertia J	0.00176 Kgm^2
DC voltage	200 V

V. CONCLUSION

The Matlab simulink model for PMSM drive and control strategy with field oriented control for different load cases is being simulated and the results are analysed. The simulation result shows the performance characteristics of PMSM, i.e. speed of the motor remains constant even with the change of load torque. The main advantage of using FOC control strategy is the independent control of speed and torque which is achieved by separately resolving and controlling the d and q axis currents.

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