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

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Abstract

A permanent Magnet Synchronous Motor is an electric motor driven by permanent magnets, finding widespread use in industrial and robotic applications due to their high efficiency, low inertia and high torque to volume ratio. Various control techniques have been implemented to make drive systems control more precise and efficient. This paper presents a Field Oriented Control (FOC) as a novel method to effectively control motor torque and speed. The primary objective of this research is to develop a detailed model of FOC-PMSM and simulate its dynamic behaviour under various operating conditions. The system is simulated in MATLAB/Simulink to check the validity, reasonability and expected outcomes. Simulation results show that the designed control system can track speed and current references with minimum error. PMSM depicts better dynamic performances with FOC implementation.

Keywords: Dynamic Performance; Field Oriented Control (FOC); MATLAB/Simulink; PMSM

1. Introduction:

DC motors dominated variable speed and drive systems ranging from low-power to high-power applications for decades due to their cheaper and simpler control mechanism. However, DC motors have significant limitations, including being uneconomical due to frequent maintenance, limited speed range of operation, lack of overload capacity and robustness, etc. [1]. At that time, AC motors were operated under a fixed grid frequency. Nowadays, AC electric-drive control systems are more widely used in various applications than DC motor systems [2]. Recent advancements in permanent magnet materials, solid-state devices and microelectronics have led to new energy-efficient and high-performance electric drives that use Brushless DC motors or PM synchronous motors. Performance comparison between these motors shows that PMSM reveals better efficiency, robustness, high power-to-weight ratio, and low noise than the BLDC motor [3]. PMSMs is a type of synchronous motor with three-phase windings on the stator and rotor fitted with permanent magnets. There is no need for slip rings and brushes as a permanent magnet in the rotor provides a magnetic field. Generally, a rare earth magnet is used as a permanent magnet of the rotor. PMSM has high performances, very good controllability in full-speed operating range, lower maintenance cost, high efficiency and low power-to-weight ratio compared to other motor types [4]. This type of motor is widely used in industrial applications, robotics and hybrid vehicles.

Various advanced control techniques are employed to optimise the performance of Permanent Magnet Synchronous Motors (PMSM) in variable speed drive applications. Some of the control techniques include field-oriented control (FOC), direct torque control (DTC), model predictive control (MPC), sliding mode control (SMC), and many more. The choice of this technique depends on the specific application, desired performance, and system complexity. The only drawback of these permanent magnet synchronous motors is the algorithms and electronics required to control the current in the motor are complex. Also, the drawback of cogging torque in PMSM can be

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eliminated through suitable design or electronic justification [5]. The technique used in this work is field-oriented control simplifies complexity and makes motor control similar to DC motors.

2. Control Strategy and Methodology:

2.1 Motor Model in “abc” Frame:

Three-phase AC fed to stator windings produces a rotating magnetic field. The rotor has a high-performance magnet to obtain a strong magnetic field such as neodymium iron boron or rare earth magnetic materials. The interaction between the rotor and stator magnetic field generates electromagnetic torque, which can be controlled by regulating the amplitude and phase of the three-phase currents. This can be achieved by using a three-phase inverter with Pulse Width Modulation (PWM) techniques. In order to facilitate analysis, the following assumptions are made: three-phase symmetrical stator winding, uniform air gap, ignoring the end effect, neglecting iron loss and magnetic saturation, linear magnetic circuit, converter provides ideal three-phase power, higher harmonics is ignored, ignoring rotor shaft friction.

Motor voltage balance equations is given by: [6]

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \frac{\partial \Psi_a}{dt} \\ \frac{\partial \Psi_b}{dt} \\ \frac{\partial \Psi_c}{dt} \end{bmatrix} \quad (1)$$

The motor flux balance equation is given by:

$$\begin{bmatrix} \Psi_a \\ \Psi_b \\ \Psi_c \end{bmatrix} = \begin{bmatrix} cos0^\circ & cos120^\circ & cos240^\circ \\ cos240^\circ & cos0^\circ & cos120^\circ \\ cos120^\circ & cos240^\circ & cos0^\circ \end{bmatrix} \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \Psi_{fr} cos\theta \\ \Psi_{fr} \cos(\theta - 120^\circ \\ \Psi_{fr} \cos(\theta - 240^\circ \end{bmatrix} \quad (2)$$

Torque expression is given by:

$$T_e = \lambda [i_a \quad i_b \quad i_c] \frac{\partial}{\partial \theta} \begin{bmatrix} \Psi_{fr} cos\theta \\ \Psi_{fr} \cos(\theta - 120^\circ) \\ \Psi_{fr} \cos(\theta - 240^\circ) \end{bmatrix} \quad (3)$$

The equation of motion for the motor is given by:

$$J \frac{d\omega}{dt} = T_e - T_l \quad (4)$$

V_a, V_b, V_c = Three phase stator voltage
i_a, i_b, i_c = Three phase stator currents
Ψ_a, Ψ_b, Ψ_c = Three phase stator winding flux
R = Resistance of stator windings
L = Inductance of stator windings
Ψ_{fr}= Rotor field flux
T_l= Load torque
λ= Motor pole number
J=rotor inertia

ω = Electrical angular velocity
Above analysis of motor in abc frame shows PMSM is a multi-variable coupled and non-linear time varying system. The direct use of traditional control cannot achieve effective control and as well system complexity is increased.

2.2 Field Oriented Control

FOC is a type of vector control in which phase and amplitude for a motor stator voltage or current vector is controlled at the same time. FOC simplifies the control of PMSM by making it to behave like a separately excited DC machine in which developed torque and magnetizing field can be controlled independently [7]. For this three-phase time variant system (abc) is converted into time invariant system (dq). This causes decoupling of Torque and flux component to make control simple. Clarke and Park transformation helps to convert abc components into dq components.

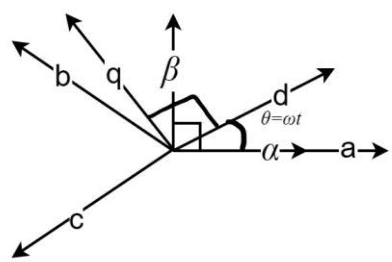

Figure 1: Reference Frame

The combined Clarke and Park Transformations can be written in Matrix form as:

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix}$$

Similarly inverse transform matrix is given by

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} \cos(\theta) & -\sin(\theta) & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{4\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$

Motor is modelled in dq frame to implement FOC technique. Modelling involves following equations [8]

$V_d = R_s i_d + L_d \frac{di_d}{dt} - L_q i_q \omega_e$-------- (1)

$V_q = R_s i_q + L_q \frac{di_q}{dt} + L_d i_d \omega_e + w_e \lambda_{af}$ --- (2)

Rearranging terms in equations, integrating them, we can obtain i_d & i_q.

$i_q = \frac{1}{L_q} \int (V_q - L_d i_d \omega_e - R_s i_q - \lambda_{af})$dt------(3)

$i_d = \frac{1}{L_d} \int (V_d + L_q i_q \omega_e - R_s i_d)$ dt------ (4)

The mechanical equations are:

$T_e = \frac{3}{2}$ P $\{\lambda_{af}\, i_q + (L_d - L_q)\,(i_d i_q)\}$ ----(5)

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

Where,

i_d = Direct Axis Stator Current in Ampere (A)

i_q = Quadrature Axis Stator Current in Ampere (A)

R_s = Stator Resistance in Ohms (Ω)

L_d = Direct Axis Inductance in Henry (H)

L_q = Direct Axis Inductance in Henry (H)

J = Moment of Inertia in Kgm^2

B = Friction Vicious Gain in Nm/rad/sec

P= number of poles

λ_{af}= Rotor Flux Constant in V/rad/sec

ω_e= Rotor's Electrical Speed in rad/sec

T_L= Load Torque in Nm

T_e= Electromagnetic Torque in Nm

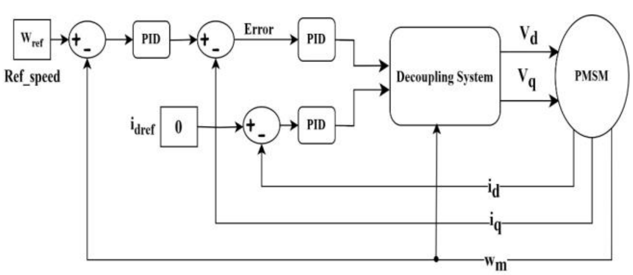

Figure 2: Implementation of FOC on PMSM

Above figure shows the general block diagram for implementation of FOC on PMSM. Motor is modelled in dq frame with use of transformations. The torque generated by motor depends on current vector $i.e. i_s = i_d + i_q$. i_d is known as flux component which is responsible for controlling flux whereas i_q is known as torque which is responsible for controlling torque. There is decoupling between these components i.e. both can be controlled independently. In this paper $i_d = 0$ is used to obtain maximum torque per ampere as similar to separately excited dc motor. Three PID controllers are tuned properly to track the reference commands under various operating conditions.

2.3 Methodology

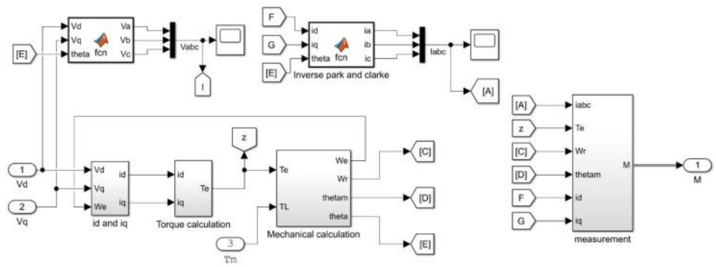

Figure 3: modeling of PMSM in dq frame

Motor is modelled in MATLAB/Simulink in dq frame using equations given as before. It is subjected to various load conditions. Motor parameters used in above model is shown in table below

Table 1: Motor parameters

Stator Resistance	0.0186875 Ω
Direct axis inductances	6.5-e3 H
Quadrature axis inductances	6.5-e3 H
Permanent Magnet flux	0.175 wb
Damping coefficient	0.001 N.m.s
Poles	8
Moment of inertia	0.008 kg.m2

These motor parameters are tested by applying FOC technique to observe the motor performances. The whole system is simulated in MATLAB/Simulink and shown in figure below.

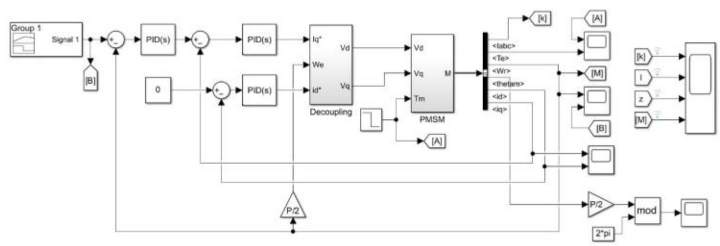

Figure 4: FOC simulation model

Since PMSM is a Multi-Input Multi-Output system, coupling exists between d-axis and q-axis. Decoupling block is used to remove the coupling between them and make system linear. This is shown in figure below.

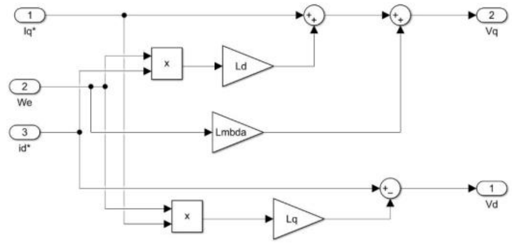

Figure 5: Decoupling block

Error signals obtained by comparing speed and current references is regulated using PID controllers to obtain i_d and i_q which eventually is fed to motor to obtain desired torque and speed. FOC method of PMSM uses three PID controllers, two of them are used to regulate d-axis and q-axis component and one is used to regulate speed. Frequency response method is used to tune PID controller with design margin=60°and crossover frequency=$\frac{2\pi f_s}{10}$

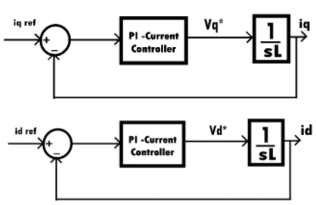

Figure 6: FOC PMSM model in dq frame

Open loop transfer function is [7]

$$G_o(s) = \frac{K_p}{LT_i}\frac{(1+sT_i)}{s^2}$$

PI Current would be

$P_i = K_p = 35.572$ $I_i = \frac{K_p}{T_i} = 128304.85$

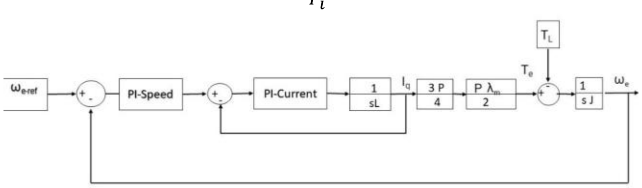

Figure 7: FOC PMSM model of Speed loop

To simplify the design of speed PI controller, one can approximate the q-current close loop transfer function to be first order system (low pass filter).

PI speed will be P_s=0.2769, I_s=107.87

3. Result and Discussion

The validity and Torque speed Response of Field Oriented Control of PMSM is examined. Motor is subjected to the variable speed at different instant of time. Reference input to the motor and output response at different instant is shown in Figure below

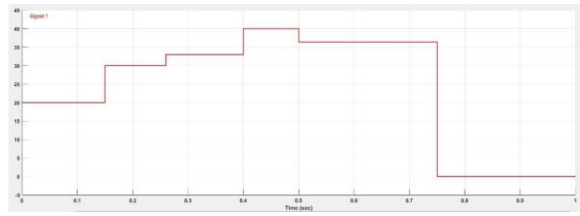

Figure 8: Speed Reference

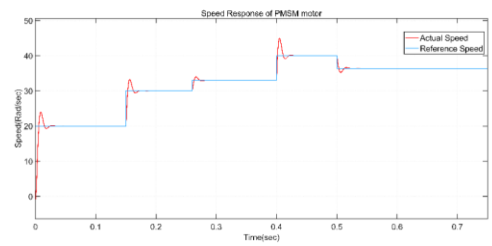

Figure 9: Speed Response

Transient response analysis of motor shows that this control technique provides better performance with minimum overshoot. This is shown as below.

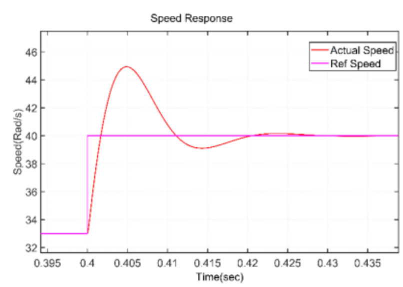

Figure 10: Transient response

Table 2: Transient response analysis

Peak Time (t_p)	4.888ms
Settling time (t_s)	29.929ms
Peak speed (C_{t_p})	44.91
Steady state speed (C_∞)	40
Overshoot	2.068%

With the proper tuning of current controllers better transient response characteristics can be obtained. Similarly, input reference Load torque to the motor shaft at different instant of time is shown below:

Table 3: Motor load

Step Time	0.4 sec
Initial Value	5 Nm
Final Value	3 Nm

For the applied load torque the electromagnetic torque response of motor is shown below.

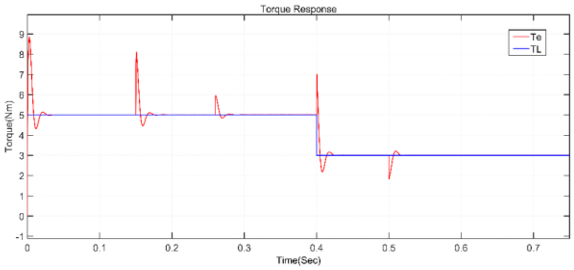

Figure 11: Torque response of motor

The transient torque response of motor with this control on varying load is given below

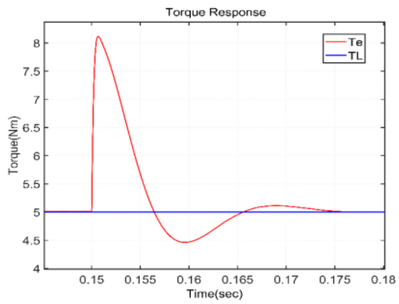

Figure 12: Transient torque response

Table below shows the transient torque analysis of motor. The performance indices shows that motor has higher overshoot and can be minimized with better PID tuning.

Table 4: Torque response analysis

Peak time (t_p)	731.975µs
Settling time (t_s)	26.185ms
Peak speed (C_{t_p})	8.121
Steady state speed (C_∞)	5
Overshoot	62.42%

4. Conclusions

Successful modelling of PMSM in dq coordinate frame and implementation of closed loop field-oriented control of PMSM using MATLAB/Simulink shows better dynamic performances of motor. Upon the various changes in reference speed and load torque to the motor at different instant of time, speed overshoot of 2.068% and torque overshoot of 62.42% with minimum settling time was observed. Moreover, maximum torque per ampere can be obtained like DC motor by making direct axis current zero. This control techniques removes the coupling terms within motor and made PMSM motor control simple and equivalent to DC motor. Highly efficient and robust PMSM can be a suitable for variable speed drives ranging from high power applications to low power applications through this control technique

5. Acknowledgement

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