Fractional Order PI Controller Based PMSM Drive under Dynamic Loading Conditions

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Abstract

Objective: The main objective of this paper is to examine the permanent magnet synchronous motor (PMSM) drive using controller under dynamics. Statistical Analysis: The method adapted for analyzing dynamics occurring in PMSM drive is fractional calculus on PI (proportional-integral) controller. The vector control scheme was applied for speed control and stimulated in MATLAB and Simulink under various operating conditions. Findings: The FOPI controlled drive shows better control execution property and robustness over traditional integer order PI controller. The dynamics during load and speed variations are figured out to be normal than the actual case by use of FOPI as speed controller. Improvement: The stimulation result shows the performance and adequacy of the proposed FOPI controlled PMSM drive system.

Keywords: Direct Torque Control, Field Oriented Control, FOPI Controller, Nelder-Mead, PMSM

1. Introduction

The permanent magnet synchronous machine has permanent magnets instead of using electromagnets in order to produce the air gap magnetic fields. Due to its significant advantages, these motors have attracted the interest of researchers and are used in many industrial applications. Newly developed PMSMs if controlled properly with high energy permanent magnet materials particularly provides fast dynamics, efficient operation and very good compatibility with their applications. The enhancement produced in permanent magnet synchronous motor drive system is due to the recent innovation in the area of microprocessor, semiconductor and magnetic materials technology. The PMSM drive in compare to the other ac drives has become a competitor because of its adjustable speed and high performance applications features. Due to possible high efficiency and compact designs, PMS motors are mainly used for battery fed drives as electric traction and in servo applications. As a result PMSM drive is widely used in general industry applications because of its high-performance control. Different control schemes have been proposed for the controlling PMSM drives. Vector control technique has been used to be one of the most effective methods. PMSM drive is controlled entirely through the stator since there is no provision of winding on rotor side for excitation. In the present work, a procedure has been developed to foretell the dynamics in PMSM drive controlled in vector quantity. The main function is carried out by d - q axis model of the PMSM to simulate and analyze the complete drive system and then the principle of vector control is used to simplify and sort out the nonlinear dynamic model and thus the dynamics are found. The main important feature is the ability to withstand disturbances in this control. Step changes in the load and reference speed are considered due to external disturbances. A high performance control system for fast dynamic response is adjusted to control variables so that the system outputs affected by any disturbances can recover to its initial status as fast as possible. The motor plays a vital role in areas of automobiles, military, precision tools, Medical instruments etc. with reference poor open-loop scalar V/Hz control, since there is no rotor coil to provide mechanical damping during transients.

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The vector control fundamentals implementation can be explained as motor phase currents $i_a$, $i_b$, and $i_c$ which are converted to $i_d$ and $i_q$ components by 3phase/2phase transformation. These are then converted into synchronous rotating frame by the unit vector component $\cos \theta$ and $\sin \theta$ before applying them to the d - q machine as shown. The controller opts two stages of inverse transformation, as shown, so that the control currents $i_d$ and $i_q$ corresponds to the motor currents $i_d$ and $i_q$, respectively. In addition, the unit vector aligns correctly to $i_d$ current with the flux vector where $i_q$ is perpendicular to it. The transformation and the inverse transformation in an inverter ideally cannot incorporate any kind of dynamics, and thus, the response to $i_d$ and $i_q$ is instantaneous.

1.1 Direct Torque Control Method

The motive of direct torque control (DTC) for PMS motor is to control the torque and flux linkage by selecting the appropriate voltage space vectors, which depends on the slip frequency and torque. The torque in PMSM is mainly controlled by adjusting the armature current based on the criteria that the electromagnetic torque is directly proportional to the armature current. The current control method is executed with the rotor reference frame which rotates with the synchronous speed for achieving high performance. Here the inductances in armature and magnet flux linkage remains constant when the back electromotive force (EMF) and variation in inductances are sinusoidal. In addition to the effects of the harmonics in inductances and back EMF which causes saturation in flux and temperature effect on the magnet, by using current control the torque response is limited with time constant of the armature winding.

1.2 Field Oriented Controlled

The main objective for controlling a PMSM drive is based on field orientation, where the magnetic flux generated from the PM rotor is fixed in respect to the rotor shaft position and the flux position in the coordinates is determined by the shaft position sensor. If $I_d=0$, the d-axis flux linkage $\theta_d$ is fixed and $\theta_q$ is made constant for a PMSM, the electromagnetic torque is then proportional to $I_q$ in closed-loop control technique. The rotor flux is produced in the q axis where as the field-oriented control is used to generate current vector. As the generated motor torque is proportionally linear to the q-axis current and d-axis rotor flux is fixed, so to achieve the maximum torque per ampere in the motor.

2. Proposed System

The PMSM drive vector control is shown in above block diagram to implement speed control strategy. The DC source is fed to IGBT inverter for providing signals to PMSM in accordance to load fluctuations with help of PWM generator. This helps to generates firing signals to IGBT’s with help of abc/d-q block which compares the three phase signals from inverter to motor and FOPI controller feedback signal. This block transforms a-b-c three phase balance signal to two phase dq0 signal and vice-versa by use of Park and Inverse Park Transformation methodology. The method transforms two-axis orthogonal stationary reference frame quantities into rotating reference frame quantities is achieved by Park’s transformation. The equations describing Park transformation is as follows:

$$ I_d = I_p \cos \theta + I_s \sin \theta $$
\[ I_q = I_\beta \sin \theta - I_\gamma \cos \theta \]

Where,
- \( I_d, I_q \) quantities are rotating reference frame
- \( I_\beta, I_\gamma \) quantities are orthogonal stationary reference frame
- \( \theta \) is the angle of rotation

The rotating reference frame quantities are transformed to two-axis orthogonal stationary reference frame using inverse Park transformation. The Inverse Park transformation is expressed by the following equations:

\[ V_\beta = V_d \cos \theta + V_q \sin \theta \]
\[ V_\gamma = V_q \cos \theta - V_d \sin \theta \]

Where,
- \( V_\beta, V_\gamma \) are orthogonal stationary reference frame quantities
- \( V_d, V_q \) are rotating reference frame quantities

3. System Modeling

3.1 PMSM Mathematical Model

In order to derive the mathematical model of PMSM, it is been divided into three quantities of axis systems, where the three-phase stationary coordinates system (A-B-C shafting coordinates), the stationary stator phase coordinates system (d-q coordinates) and the rotor two-phase rotating coordinate system (d-q coordinate system). Therefore, the above coordinate system is represented as follow:

The PMSM voltage equations in the d-q coordinate system are given in equations (1) and (2).

\[ V_d = R_s i_d + L_s \frac{di_d}{dt} - \omega_r N_p \lambda_r \sin \theta_r \]
\[ V_q = R_s i_q + L_s \frac{di_q}{dt} + \omega_r N_p \lambda_r \cos \theta_r \]

From equations (1) and (2), we get

\[ \frac{di_d}{dt} = \frac{-R_s}{L_s} i_d + \frac{N_p \lambda_r}{L_s} \sin \theta_r + \frac{U_d}{L_s} \]
\[ \frac{di_q}{dt} = \frac{-R_s}{L_s} i_q - \frac{N_p \lambda_r}{L_s} \cos \theta_r + \frac{U_q}{L_s} \]

In control systems, the sampling cycle is of shorter duration of time. Thus each sampling period is considered to be constant. So, the next equations are given in (5) and (6).

\[ \frac{d\omega_r}{dt} = 0 \] \hspace{1cm} (5)
\[ \frac{d\theta_r}{dt} = \omega_r \] \hspace{1cm} (6)

Above, \( V_d - V_q \) and \( i_d - i_q \) represent d and q the axis voltages and currents respectively. \( R_1 \) and \( L_1 \) are the equivalent phase resistance and inductance of the stator of the PMSM's. \( N_p \) is the number of poles in motor, \( \lambda_r \) is the rotor flux, \( \omega_r \) represents the rotor mechanical angular velocity and \( \theta_r \) is the rotor angular position.

3.2 FOPI Controller Mathematical Model

The use of fractional controller in the field of dynamic control systems is increased. Fractional order control systems and controllers are described by a set of differential equations. The fractional integro-differential equation of the FOPI controller in frequency domain is given by

\[ u(t) = K_p e(t) + K_i \int_0^t e(t) \, dt \]

Where \( K_p \) and \( K_i \) denotes the proportional, integral, and fractional order of the FOPI controller respectively.

The transfer function of the FOPI controller can be obtained for a continuous system through Laplace transformation as:

\[ G_c(s) = \frac{K_p + \frac{K_i}{s^\alpha}}{s^\alpha} \] \hspace{1cm} (8)

From (8), it is clear that the FOPI controller involves three parameters (\( K_p, K_i, \) and \( \alpha \)) to tune, since the fractional order \( \alpha \) is not necessarily integer.

To represent FOPI controller in frequency domain \( s \) is substitute as \( s = j\omega \) into (8):

\[ G_c(j\omega) = \frac{K_p + \frac{K_i}{(j\omega)^\alpha}}{(j\omega)^\alpha} \]

Therefore the convenient form is written as:

\[ (j\omega)^\alpha = \omega^\alpha(\cos \gamma j + j \sin \gamma j), \quad \gamma = \frac{\pi \alpha}{2} \] \hspace{1cm} (10)

The FOPI controller is represented in terms of the complex equation by substituting (10) into (9);

\[ G_c(j\omega) = \frac{K_p + \frac{K_i \cos \gamma j}{\omega^\alpha}}{\omega^\alpha} \]

4. Tuning Technique

The parameters of the controller are tuned by optimizing the response with a constraint on different conditions of...
load to output in order to maintain maximum sensitiv-
ity. In this paper, Nelder-Mead (N-M) method is used
to tune α to get optimal values of controller for different
conditions of loading.

Nelder- Mead Algorithm - The technique keeps up
at each progression a non-decline simplex, a geometric
figure in n measurements of nonzero volume that is the
curved structure of n + 1 vertices. Every emphasis starts
with a simple, determined by its n+1 vertex what’s more,
the related capacity values. At least one test focuses are
processed alongside their capacity values and the emphasis
ends with limited level sets. In MATLAB, Nelder–Mead
calculation has been characterized by a standard capacity
fminsearch() which shows the algorithm as follows:

Step 1: Function value is sorted to satisfy the order of
vertices $f_1 < f_2 < \ldots < f_{n+1}$

Step 2: Calculation of $x_m = \text{sum } x_i$ (average of all the
points excluding the worst)

Step 3: Computation of reflection point as
$x_r = x_m + R(x_m - x_{n+1})$ and evaluate $f(x_r)$. If $f_r$ less than $f_1$ and $f_n$ accept
$x_r$ and terminate the iteration (Reflection).

Step 4: If reflection point $f_r$ less than $f_1$ then calculate
$x_e = x_m + K (x_m - x_{n+1})$ and evaluate function $f(x_e)$. If $f_e$ less
than $f_r$ accept $x_e$; or accept $x_r$ otherwise terminate the
iteration (Expansion).

Step 5: If reflection point $f_r$ greater than $f_n$, perform
a contraction between $x_m$ and the better of $x_i$ and $x_{(n+1)}$
(Contraction).
(a) If $f_r$ lies as follows; $f_r < f_1 < f_{n-1}$ then calculate
$x_c = x_m + K (x_m - x_{n+1})$ and evaluate $f(x_c)$. If $f_c$ greater than $f_r$
then accept $x_c$ and terminate the iteration; or make a
shrink (Outside).
(b) If $f_r$ greater than $f_{n+1}$, calculate
$x_i = x_m - K (x_m - x_{n+1})$ and
calculate function $f(x_i)$. If $f_i$ less than $f_{n+1}$ accept $x_i$
and terminate the iteration; or make a shrink (Inside).

Step 6: Evaluation of function $f$ at the n points $v_i = x_i +
S (x_i-x_1), i = 2 \ldots n+1$. The vertices of the simplex points at
the next iteration are $v_1, v_2 \ldots v_{n+1}$ (Shrink).

5. Result Analysis
The introduction of FOPI plant on PMS motor drive has
been analyzed and simulations have been done in the
MATLAB/SIMULINK version 2014b environment. The
PMSM drive with FOPI controller using PSO algorithm
are also simulated in MATLAB. The three different cases
are simulated under the different settings to compare the
performance of speed coordinated control.

Case (i): The motor speed is a step signal with magni-
tude is 500 rpm. The machine was stimulated at No-load
in the start-up stage for a period of 1sec and following
waveforms were plotted;
From figure, it is seen that voltage fed to the PMSM drive is in pulsed three phase in nature and current output from motor is normal after 0.1sec of its operation respectively. Figure also depicts speed attained by PMSM drive is steady with one overshoot followed by an undershoot and the electromagnetic torque also settles before 0.1 sec of its normal operation respectively.

Case (ii): in this case also speed of motor is a step signal made to run at 500 rpm. The motor was stimulated at constant load of 2 Nm as a step signal for a period of 1sec and following waveforms were plotted;

Case (iii): The speed of the motor is a step signal which magnitude is 500 rpm. The dynamic load from 2 Nm to 4 Nm was introduced in motor for a period of 2sec dynamics were occurred at 1sec and following waveforms were plotted;
Figure 4. Under Dynamic Loading condition.

From figure, it is seen that no voltage fluctuations occur during change in load at 1sec and current output from motor changes from 2A to 4A at 1sec during operation respectively. Figure shows there is slight dip in speed when load dynamics occur at step time of 1sec and the electromagnetic torque remains undisturbed during transient operation respectively.

Case (iv): The initial speed of the motor was a step signal of magnitude 500 rpm and then dynamically changed to 600rpm at 1sec for a load of 2 Nm which was stimulated for a period of 2sec and following waveforms were plotted;

From figure, it is seen that voltage gap occurs during change in speed and current output from motor gets distorted at 1sec during operation respectively. Figure shows that when the speed is increased there is no overshoots and undershoots and the electromagnetic torque shows distorted for less duration of time for step time at 1sec respectively.

Figure 5. Under Dynamic Speed Varying condition.

6. Conclusion and Future Scope

In this paper, Fractional order PI controller introduction for PMSM drive of industrial applications was designed, modeled and stimulated under various conditions of loading and speed variation occurring in the working environment of PMSM motor was found to be optimized. From the simulation studies, it can be concluded that the tuning by N-M method performs better than other optimisation techniques with respect to consistency. The tuning of FOPI using Nelder Mead gives accurate
response and allows contingency analysis in system performance in real time implementation. This researched can be pursued for further enhancement of other real time approaches in the working environment of various motors used in industries and robotics.

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