Vector control of permanent magnet synchronous motor drive using DSP controller

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Abstract

PMSM drive with high dynamic response, is the attractive solution for servo applications like robotics, machine tools, electrical vehicles etc. Vector control is the widely accepted strategy for PMSM control, which enables decoupled control of torque and flux, thus improving the transient response of torque and speed. As vector control demands exhaustive real time computations, so the present work is implemented using TI DSP 320C240. Presently position and speed control have been successfully implemented. The feedback information used is shaft (rotor) position from the incremental encoder and two line currents. We conclude with the hope to extend the present experimental setup for further research related to PMSM applications.

Nomenclature

\( i_{\alpha}, i_{\beta}, i_{\gamma} \)  Stator line currents
\( i_{a}, i_{b}, i_{c} \)  Stator current in alpha-beta axis
\( i_{ld}, i_{sq} \)  Stator current in d-q axis.
\( u_{ld}, u_{sq} \)  Stator voltages in d-q axis.
\( R_{s} \)  Stator resistance per phase.
\( L_{l} \)  Stator leakage inductance per phase
\( P \)  Number of poles.
\( \omega_{e} \)  Angular speed in electrical radians/sec.
\( \omega \)  Angular speed in mechanical radians/sec.
\( e \)  Instantaneous rotor position wrt stator reference frame in electrical radians.
\( K_{e} \)  Back emf constant.
\( K_{t} \)  Torque constant.
\( m_{d} \)  Electromechanical torque.
\( m_{q} \)  Load Torque.
\( J \)  Moment of inertia.

1. Introduction

Until few years ago, DC motor drives remained the only choice for fast response, high performance drives. This is because DC machine have two separate physical windings, the armature and field whose MMFs are always at right angles with respect to each other in space, therefore armature control can be done independent of field control, yielding fast response torque and speed control. AC machines due to their many advantages such as better power/weight ratio, lower inertia, higher speeds and low maintenance are always the favourites of industry, but due to coupling between torque and flux control the control strategy is complicated.

It was later realized that if the modelling of the AC machine is done analogous to a DC machine, it will decouple the control of flux and torque. This will lead to performance similar to DC motor. This technique came to be known as vector control or field orienter control of AC motors.

1(a) Conventional block diagram of a motor drive.

The block diagram of the closed loop control of motor drive can be seen in Fig.1.


The concept of vector control lies in the proper space phasor modelling of the AC machine. To have the same analogy of the DC machine, all stator parameters are to be transformed in rotor reference frame. The control parameters will be pure DC and machine will give performance same as DC machine.

2(a) Transformation of stator current from stator reference frame to rotor reference frame.

Transformation of stator currents from stator reference frame to rotor reference frame is done in two steps. Firstly 3phase currents are resolved to 2phase system, followed by transformation to rotor coordinates by use of rotor position information.
Fig. 2 is used to derive the required transformation equations. Here phase 'a' is taken as reference in stator coordinates and d-axis is taken as reference for rotor coordinates. Alpha axis is kept same as phase 'a' axis.

Transformation equation from 3-phase to its corresponding 2-phase are,

\[
i_{sa} = \frac{2}{3} i_{s1}
\]
\[
i_{sb} = \frac{\sqrt{3}}{2} (i_{s2} - i_{s3})
\]

and corresponding reverse transformation equations are,

\[
i_{s1} = \frac{2}{3} i_{sa}
\]
\[
i_{s2} = -\frac{1}{3} i_{sa} + \frac{1}{\sqrt{3}} i_{sb}
\]
\[
i_{s3} = -\frac{1}{3} i_{sa} - \frac{1}{\sqrt{3}} i_{sb}
\]

Now alpha-beta components of currents from stator reference frame are to be transformed to rotor reference frame i.e. d-q axis. This needs the instantaneous rotor position information. Transformation equations from alpha-beta axis to d-q axis are,

\[
i_{sd} = i_{sa} \cos \epsilon + i_{sb} \sin \epsilon
\]
\[
i_{sq} = i_{sb} \cos \epsilon - i_{sa} \sin \epsilon
\]

and corresponding reverse transformation equations are,

\[
i_{sa} = i_{sd} \cos \epsilon - i_{sq} \sin \epsilon
\]
\[
i_{sb} = i_{sd} \sin \epsilon + i_{sq} \cos \epsilon
\]

2(b) Dynamic model of PMSM.

For deriving the dynamic model space phasor transformations for stator voltages, stator flux linkages, rotor currents etc has to be derived and after manipulation we finally arrive at a set of equation which represent complete dynamic model of the PMSM. They are

\[
u_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} - \omega_s L_s i_{sq}
\]
\[
u_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + \omega_s L_s i_{sd} + K_F \omega_s
\]
\[
m_d = K_T i_{sq}
\]
\[
j \frac{d\omega}{dt} = K_T i_{sq} - m_L
\]
\[
\frac{d\omega}{dt} = \omega = \omega_s
\]
3(a) Operational Control strategy

In correspondence to the voltage equation derived the phasor diagram of the PMSM is shown in fig.3. In PMSM the air gap flux is equal to magnet flux and the electromagnetic torque is derived from the magnet flux only, with no reluctance torque.

Speed control from zero to base speed requires constant torque operation and for that air gap flux has to be held constant. The same can be achieved if we apply stator currents in quadrature axis only, keeping its d-axis component as zero. The phasor diagram for constant torque mode operation is drawn in fig.4. From the figure it can be seen that stator voltage applied increases with speed with constant torque on the machine.

Block diagram for the overall closed loop system of the PMSM drive implemented can be seen in fig.5

![Fig 3: Phasor diagram of PMSM model](image)

![Fig 4: Phasor diagram of PMSM under constant torque mode](image)

3(b) Controller design.

For operation of the PMSM under closed loop control mode there should be one speed controller which will generate the current reference and this current reference will be the set point to the q-axis current axis controller. For the constant torque mode the d-axis current reference is kept as zero.

(a) Current controller design.

D-axis voltage equation is

\[ u_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} - \omega_s L_m i_{sq} \]

\[ u_{sd} = u_{sd, ref} - \omega_s L_m i_{sq} \]

If we take \( u_{sd, ref} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} \) as the current controller output, then the current controller response is decoupled from the effect of q-axis current.

In the similar way Q axis voltage equation is

\[ u_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + \omega_s L_m i_{sd} + K_F \omega_s \]

\[ u_{sq} = u_{sq, ref} + \omega_s L_m i_{sd} + K_F \omega_s \]

If we take \( u_{sq, ref} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} \) as the current controller output, then the current controller response is decoupled from the effect of d-axis current.

Here PI controllers are used for both the q-axis and d-axis controllers.

(b) Speed controller.

The controller used for speed controller is again a PI controller.

Structure used for the PI controller is,

\[ K_p \frac{1 + Ts}{s} \]

It is realised in the digital domain with limiters as

\[ Un = K_p [ En + \frac{1}{2 \frac{Ts}{T} (E_n + E_{n-1})} + I_{n-1} ] \]

3(c) Normalisation of equations.

Since the DSP used is a fixed point processor, variables are needed to be per unitised to make it easy to implement on a DSP. For example the normalisation of plant equation is presented below.

Generally motor equation is represented as

\[ V = R i + L \frac{di}{dt} + E \]

Dividing both sides by \( V_b \) (base value) will perunitize the equation as,

\[ \frac{V}{V_b} = \frac{R}{V_b} i + \frac{L}{V_b} \frac{di}{dt} + \frac{E}{V_b} \]

\[ V_{pu} = \frac{R}{Z_b} i + \frac{\omega_s L}{Z_b} \frac{di}{dt} + \frac{E}{V_b} \]

\[ V_{pu} = R_{pu} i_{pu} + X_{pu} \frac{di_{pu}}{dt} + e_{pu} \]
**fig. 5. Overall block diagram for vector control of PMSM drive.**

**4(a) Power circuit description.**

Power circuit block diagram for the hardware setup is shown in fig. 6.

It includes:
1. PMSM machine attached with an incremental encoder.
2. 3-phase IGBT based 10kVA inverter.
3. TMS320F240 DSP based digital controller platform.

**4(b) Organisation of DSP hardware platform.**

Organisation of the DSP platform can be seen in fig. 8. It comprises of four hardware modules.

1. An analog signal conditioning board.
2. A DSP board.
3. A position encoder interface.
4. A power converter interface.

DSP platform shown is designed in house which can execute complex algorithms needed in power electronics at high sampling frequencies. The feedback information taken for the control are:
- Two line currents and instantaneous rotor position from incremental encoder.
- Scaling done for line current feedback.
- ADC's of F240 processor are unipolar and operate between 0 to 5V and since the current sensor outputs from the power circuit are in the range of +/-10V, these signals need to be properly scaled. This scaling is done in the analog signal conditioning card, which scales +/-10V signal to exactly 0 to 5V.

**Incremental encoder interface.**

For determining the rotor position with respect to the stator, an incremental position encoder is mounted on the machine shaft. It gives 1440 pulses/mechanical rev i.e., resolution of 0.25 degrees. The encoder generates two train of pulse through
its two quadrature pulse channels and one index pulse through the third channel. It is mounted in such a way that when magnet axis coincides with stator phase or coil axis, the index pulse is generated. This is required for proper alignment. Pulses generated from encoder are used as clock for one of the timer, where a counter is updated at each rising edge. It is incremented/decremented depending upon the direction. So from the count value of the counter the exact position of the rotor can be found out.

Figure 7 shows the waveforms generated.

4(c) Software Program Organisation.

Software program is organised in the following way.
- Initialize CPU
- Initialize processor
- Initialize interrupt
- Main loop (synchronized to sampling interrupt)
  - Read position
  - Read currents
  - Compute speed
  - Execute position loop
  - Execute speed loop
  - Transform currents from stator to rotor reference frame
  - Execute current loop
  - Transform from rotor to stator reference frame
  - Update PWM
  - Wait for Interrupt
  - Go to main loop.

Figure 6 shows the organisation of the digital control hardware.
5 Experimental results.

In this section, experimental results are presented. They are all taken for alternate reversals of speed so that close performance comparison can be done. Figure 9(a) shows the \( \text{lsq\_ref} \) and actual \( \text{lsq} \) component of stator current at speed reversal (current controller response). Figure 9(b) shows the \( \text{Ws\_ref} \) and actual \( \text{Ws} \) at speed reversal (Speed controller response).

Figure 9(c) shows the alpha and beta component of stator current at speed reversal. Figure 9(d) shows the D-axis and q-axis components of stator current at speed reversal. Figure 9(e) shows the sine(position) and cosine(position) at speed reversal. Figure 9(f) shows the actual speed and epsilon(position) at speed reversal.
6 Conclusion.

In this paper a vector control based speed control has been presented. The present work is concluded with the hope that it can be extended for more sophisticated applications of PMSM control.

7 References

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