DSP Based Control of PMSM

Spr494, Spra588
Motor Types (Overview)

Electric Motor types

AC
- Asynchronous
  - Induction
  - PMSM
  - BLDCM
- Synchronous
  - Switched Rel
  - Stepper

DC

PMSM

- The permanent magnet synchronous motor (PMSM) is a PM motor with a sinusoidal back-EMF.

- **Compared** to the BLDC motor, it has less torque ripple because the torque pulsations associated with current commutation do not exist.
PMSM Motor Features

- Simple structure, smaller size, lighter weight
- No brush/commutator, better than DC motor
- No flux excitation current, better than Induction motor
- High efficiency, high power factor, large torque
PMSM

- A carefully designed machine in combination with a good control technique can yield a very low level of torque ripple (<2% rated),
  - which is attractive for high-performance motor control applications such as machine tool and servo applications.
Target Applications

- Industrial
- Consumer
- Servo
- Automobile
- Medical
- Robotic
- Lift/Elevator
- Oilfield
Commutation

- **Trapezoidal Commutation**
  - Enough performance to control low dynamic motors
  - Less System costs
    - sensorless control (BEMF-detection)
    - less CPU resources due to defined commutation points (least 6 points)
    - easy and fast implementation
Commutation

- **Sinusoidal Commutation**
  - Higher performance to control mid dynamic motors
  - Sinusoidal weighted PWM (75%) Space Vector Modulation (Higher efficiency 86%),
  - Better torque management
    - better startup performance, constant torque, less torque ripple (low/mid speed)
    - improved dynamical reaction
System Control

- **Field Orientation Control**
  - Improved torque management
    - Less System costs by controlling the current space vectors directly in the frame of the rotor
    - Providing smooth and constant torque over the whole speed range
  - Perfect for control of high dynamic motors

- **Direct Torque Control**
  - Simple and easy to implement
  - Torque ripple
  - Side effect of stator resistor at low speed
Model of PMSM in a-b-c Reference Frame

- Figure depicts a cross-section of the simplified three-phase surface mounted PMSM motor.
Model of PMSM in a-b-c Reference Frame

- The stator windings, as-as’, bs-bs’ and cs-cs’ are shown as lumped windings for simplicity, but are actually distributed about the stator.
- The rotor has two poles.
- Mechanical rotor speed and position are denoted as $\omega_{rm}$ and $\theta_{rm}$, respectively.
- Electrical rotor speed and position, $\omega_r$ and $\theta_r$, are defined as $P/2$ times the corresponding mechanical quantities, where $P$ is the number of poles.
Model of PMSM in a-b-c Reference Frame

Based on the above motor definition, the voltage equation in the a-b-c stationary reference frame is given by

\[ V_{abcs} = R_s i_{abcs} + \frac{d}{dt} \lambda_{abcs} \]

where

\[ f_{abcs} = [f_a \ f_b \ f_c]^T \]

and the stator resistance matrix is given by

\[ R_s = \text{diag}[r_s \ r_s \ r_s] \]
Model of PMSM in a-b-c Reference Frame

- The flux linkages equation can be expressed by

\[
\lambda_{abcs} = L_s i_{abcs} + \lambda_m' \begin{bmatrix}
\sin \varphi_r \\
\sin(\varphi_r - \frac{2\pi}{3}) \\
\sin(\varphi_r - \frac{4\pi}{3})
\end{bmatrix}
\]

where \( \lambda_m' \) denotes the amplitude of the flux linkages established by the permanent magnet as viewed from the stator phase windings.

- Note that the back-EMFs are sinusoidal waveforms that are 120° apart from each other.
Model of PMSM in a-b-c Reference Frame

- The stator self inductance matrix is given as

\[
L_s = \begin{bmatrix}
L_{ls} + L_A - L_B \cos 2\theta_r & -\frac{1}{2} L_A - L_B \cos 2(\theta_r - \pi / 3) & -\frac{1}{2} L_A - L_B \cos 2(\theta_r + \pi / 3) \\
-\frac{1}{2} L_A - L_B \cos 2(\theta_r - \pi / 3) & L_{ls} + L_A - L_B \cos 2(\theta_r - 2\pi / 3) & -\frac{1}{2} L_A - L_B \cos 2(\theta_r + \pi) \\
-\frac{1}{2} L_A - L_B \cos 2(\theta_r + \pi / 3) & -\frac{1}{2} L_A - L_B \cos 2(\theta_r + \pi) & L_{ls} + L_A - L_B \cos 2(\theta_r + 2\pi / 3)
\end{bmatrix}
\]

- The torque and speed are related by the electromechanical motion equation

\[
J \frac{d}{dt} \omega_{rm} = \frac{P}{2} (T_e - T_L) - B_m \omega_{rm}
\]
Model of PMSM in Rotor Reference Frame

- The voltage and torque equations can be expressed in the rotor reference frame in order to transform the time-varying variables into steady state constants.
- Since the stator has two poles and the rotor has four poles, the transformation of the three-phase variables in the stationary frame to the rotor reference frame is defined as

\[ f_{qd0r} = K_r f_{abcs} \]

where

\[
K_r = \frac{2}{3} \begin{bmatrix}
\cos \theta_r & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\
\sin \theta_r & \sin(\theta_r - \frac{2\pi}{3}) & \sin(\theta_r + \frac{2\pi}{3}) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]
Model of PMSM in Rotor Reference Frame

- If the applied stator voltages are given by

\[
\begin{align*}
V_{as} &= \sqrt{2} V_s \cos \theta_{ev} \\
V_{bs} &= \sqrt{2} V_s \cos (\theta_{ev} - \frac{2\pi}{3}) \\
V_{cs} &= \sqrt{2} V_s \cos (\theta_{ev} + \frac{2\pi}{3})
\end{align*}
\]

- Then we have

\[
\begin{align*}
v_{qs}^r &= r_s i_{qs}^r + \omega_r \lambda_{ds}^r + \frac{d}{dt} \lambda_{qs}^r \\
v_{ds}^r &= r_s i_{ds}^r - \omega_r \lambda_{qs}^r + \frac{d}{dt} \lambda_{ds}^r \\
\lambda_{qs}^r &= L_{qs} i_{qs}^r \\
\lambda_{ds}^r &= L_{ds} i_{ds}^r + \lambda_m^r
\end{align*}
\]
Model of PMSM in Rotor Reference Frame

- The electromagnetic torque can be written as

\[
T_e = \frac{3}{2} P \left[ \lambda_m^r i_q^r + (L_{ds} - L_{qs}) i_q^s i_d^s \right]
\]

- it can be seen that torque is related only to the d- and q-axes currents.

- Since \( L_q \geq L_d \) (for surface mount PMSM, both of inductances are equal), the second item contributes a negative torque if the flux weakening control has been used.
In order to achieve the maximum torque/current ratio, the d-axis current is set to zero during the constant torque control so that the torque is proportional only to q-axis current.

Hence, this results in the control of q-axis current for regulating the torque in rotor reference frame.
Based on the above analysis, a PMSM drive system is developed as shown:

The total drive system looks similar to that of the BLDC motor and consists of a PMSM, power electronics converter, sensors, and controller.
PMSM Machine

- The design consideration of the PMSM is to first generate the sinusoidal back-EMF.

- Unlike the BLDC, which needs concentrated windings to produce the trapezoidal back-EMF, the stator windings of PMSM are distributed in as many slots per pole as deemed practical to approximate a sinusoidal distribution.

- To reduce the torque ripple, standard techniques such as skewing and chorded windings are applied to the PMSM.
**PMSM Machine**

- With the sinusoidally excited stator, the rotor design of the PMSM becomes more flexible than the BLDC motor where the surface mount permanent magnet is a favorite choice.

- Besides the common surface mount non-salient pole PM rotor, the salient pole rotor, like inset and buried magnet rotors, are often used because they offer appealing performance characteristics during the flux weakening region.
PMSM Machine

- A typical PMSM with 36 stator slots in stator and four poles on the rotor is shown in Fig.

A four-pole 24-slot PMSM.
Power Electronic Converter

- The PMSM shares the same topology of the power electronics converter as the BLDC motor drive system.

- The converter is the standard two-stage configuration with a dc link capacitor between a front-end rectifier and a three-phase full-bridge inverter as the output.

- The rectifier is either a full-bridge diode or power switch rectifier.
Due to the sinusoidal nature of the PMSM, control algorithms such as $V/f$ and vector control, developed for other AC motors, can be directly applied to the PMSM control system.

If the motor windings are Y-connected without a neutral connection, three phase currents can flow through the inverter at any moment.
With respect to the inverter switches, three switches, one upper and two lower in three different legs conduct at any moment as shown:
Power Electronic Converter

- PWM current control is still used to regulate the actual machine current.

- Either a hysteresis current controller, a PI controller with sine-triangle, or a SVPWM strategy is employed for this purpose.

- Unlike the BLDC motor, the three switches are switched at any time.
Sensors

- There are two types of sensors used in the PMSM drive system:
  - the current sensor, which measures the phase currents,
  - and the position sensor which is used to sense the rotor position and speed.

- Either an encoder or resolver serves as the position sensor.
- Rotor position is needed in order to synchronize the stator excitation of the PMSM with the rotor speed and position.
Sensors

- the structure of an optical encoder.
Sensors

- It consists of a light source, a radially slotted disk and photoelectric sensors.
  - The disk rotates with the rotor.
  - The two photo sensors detect the light passing through the slots in the disk.

- When the light is hidden, a logic “0” is generated by the sensors.

- When the light passes through the slots of the disk, a logic “1” is produced.
Sensors

- By counting the number of pulses, the motor speed can be calculated.
- The direction of rotation can be determined by detecting the leading signal between signal A and signal B.
Sensors

- A resolver is a rotary electromechanical transformer.

- It outputs to sinusoidal signals such that one wave is a sinusoidal function of the rotor angle $\theta$, while the other signal is a cosinusoidal function of $\theta$.

- The difference between these two waveforms reveals the position of the rotor.

- Integrated circuits such as the AD2S80 can be used to decode the signals.
Sensors

- The resolver output waveform and the corresponding rotor position:
Controller

- The interface of the LF2407:

```
| ia  | ADCIN0 |
| ib  | ADCIN1 |
| θ   | ADCIN2 |
```

TMS320LF2407

Gate Drive

PWM-1 & PWM-6
Controller

- Similar to the BLDC motor control system, three input channels are selected to read the two phase currents and resolver signal.
- Because a resolver is used in one case, the QEP inputs are not used.
- QEP inputs work only with a QEP signal that a rotary encoder supplies.
- The DSP output pins PWM1-PWM6 used to supply the gating signals to the switches and form the output of the control part of the system.
Implementation of the PMSM System

- A block diagram of the PMSM drive system:
Major Control Requirements

- **Measurement of phase current**
  - 2 synchronous converting ADC / or
  - Using single DC Link Shunt

- **Transformation (Phase current)**
  - Clark Transformation
  - Park Transformation

- **Generation of the rotating field**
  - PWM unit
  - Space Vector modulation

- **Start of the motor**
  - Rotor stalled
  - Rotating

- **PI Controller**
  - Speed
  - Current (Torque)
Measurement of Phase Current (1)

For FOC a continuous three phase current information is needed.
2 synchronous converting ADC:
- Can be realized with two ADC
Measurement of Phase Current (2)

For FOC a continuous three phase current information is needed.

DC Link Shunt Measurement:

- Can be realized with one ADC channel
- Needs to know the actual switching pattern
Method to Measure DC Link Current

Timer T12 / CAPCOM6

CC61R

CC60R

Channel 0 (CC60)
Implementation of the PMSM System

- The control program of the PMSM has one main routine and includes four modules:
  1. Initialization procedure
  2. DAC module
  3. ADC module
  4. Speed control module
Implementation of the PMSM System
The Speed Control Algorithm

- In the PM synchronous motor control system the Timer 1 underflow interrupt is used for the subroutine of speed control.

- This routine performs the tasks of:
  - Reading the current and position signal, then generating the commanded speed profile.
  - Calculating the actual motor speed, transferring the variables in the \( abc \) model to the \( d-q \) model and reverse.
  - Regulating the motor speed and currents using the vector control strategy.
  - Generating the PWM signal based on the calculated motor phase voltages.

- The PWM frequency is determined by the time interval of the interrupt, with the controlled phase voltages being recalculated every interrupt.
The Speed Control Algorithm

- The code below shows this routine.

```
T1_PERIOD_ISR:
; Context save regs
MAR   *,AR1 ; AR1 is stack pointer
MAR   *+ ; skip one position
SST #1,*+ ; save ST1
SST #0,*+ ; save ST0
SACH *+ ; save acc high
SACL * ; save acc low
POINT_EV
SPLK #0FFFFh,EVIFRA ; Clear all Group A interrupt flags (T1 ISR)
```
The Speed Control Algorithm

READ_SIG

CALL ADC_CONV
CALL CAL_TRIANGLE
CALL ADC_DQ

POINT_B0

LACC CL_SPD_FLG
BCND CURRENT_CNTL,GT ;speed-loop?

; speed control

SPEED_CNTL: POINT_B0

CALL SPEED_PROFILE
CALL VTIMER_SEC
CALL SPEED_CAL
CALL D_PID_spd
BLDD #D_PID_out ;iqsr
SPLK #0, idsr_ref
The Speed Control Algorithm

; current control
CURRENT_CNTL
    CALL    D_PID_cur
    BLDD    #D_out_iq, Vqr
    BLDD    #D_out_id, Vdr
    CALL    DQ_ABC
    BLDD    #a_out, Va
    BLDD    #b_out, Vb
    BLDD    #c_out, Vc
PWM_GEN
    CALL    PWM_DRV
DA_CONV
    CALL    DAC_VIEW_Q15I
The Speed Control Algorithm

;Restore Context

END_ISR:

    MAR *, AR1 ; make stack pointer active
    LACL *- ; Restore Acc low
    ADDH *- ; Restore Acc high
    LST #0, *- ; load ST0
    LST #1, *- ; load ST1
    CLRC INTM
    RET
The Calculation of \( \sin \theta \) and \( \cos \theta \)

- A lookup table is used to calculate the sine and cosine values of the rotor position \( \theta \).
- The rotor electrical angle depends only on its sine value in lookup table.
- The cosine value is calculated by shifting the sine value 90 degrees.
- The sine and cosine values, which are used in the transformation, can be obtained by simply knowing the rotor angle.
The Calculation of $\sin \theta$ and $\cos \theta$

- The code below shows how to read the 1:1 look-up table with the LF2407.

```
TRI_CAL
...
LACC TRI_INT ;load accumulator
AND #0ffh ;get lower bits
ADD #SINTAB ;table read
TBLR sine_a
...
RET
```
The Calculation of $\sin\theta$ and $\cos\theta$

- The block of code below shows a portion of the sine value lookup table.

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<th>Index</th>
<th>Angle</th>
<th>$\sin(\text{Angle})$</th>
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<tr>
<td>24</td>
<td>33.75</td>
<td>0.5556</td>
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</table>

... RET
The abc-to-dq Transformation

- The abc-to-dq transformation transfers the three-phase stationary motor model to a two-phase rotational motor model.
- In other words, under the restriction of the same motor performance, three phase stationary stator windings with $120^0$ separation can be replaced by a two-phase rotational winding with the $q$-phase $90^0$ ahead of $d$-phase.
- The two-phase currents are related to the three-phase currents as defined by the transformation. After this transformation, a significant simplification is achieved.
- The $d$ and $q$-axis variables are decoupled and independent with time and rotor position, which implies that these variables become constant in steady state.
The abc-to-dq Transformation

- It is possible to control the d and q variables independently.
- Since the d-axis variables are associated with the field variable and q-axis variables are related to the torque, this feature enables us to control the ac motor similar to a dc motor.
- For more detailed information on this topic we can refer to vector control theory.
The abc-to-dq Transformation

A portion of the abc-to-dq transformation using the assembly code is given in the code below:

```
ABC_DQ:
...
    LACC   #0
    LT    ABC_ain
    MPY    sone_a
    LTA    ABC_bin
    MPY    sone_b
    LTA    ABC_cin
    MPY    sone_c
    LTA    ABC_ain
    SACH   ABC_D_out
...
RET
```
The d-q to a-b-c Transformation

- After the commanded d and q-axes variables are calculated, these two variables are transferred to the a-b-c stationary frame to drive the motor. This reverse transform is defined as follows:

\[ f_{abc} = K_r f_{qd0r} \]

- where

\[
K'_r = \begin{bmatrix}
\cos\vartheta_r & \sin\vartheta & 1 \\
\cos(\vartheta_r - \frac{2\pi}{3}) & \sin(\vartheta_r - \frac{2\pi}{3}) & 1 \\
\cos(\vartheta_r + \frac{2\pi}{3}) & \sin(\vartheta_r + \frac{2\pi}{3}) & 1 \\
\end{bmatrix}
\]
The d-q to a-b-c Transformation

- An example of the assembly code to implement the above equation is given in the code below:

```assembly
DQ_ABC
...
...
LACC  #0
LT    DQ_D_ref
MPY   sone_a
LTa   DQ_Q_ref
MPY   cosone_a
MPYA  cosone_b
SACH  DQ_aout
...
...
RET
```
The PWM circuits of the 2407 Event Manager are used to generate the gating signals.

Figure displays the principle of this method.
PWM Generation

- The control signal with frequency $f_1$ is constantly compared with a triangle signal which has a high-frequency $f_2$ (usually $f_2/f_1 > 21$).

- If the controlled signal is larger than the triangle signal, a PWM output signal becomes a logic “1”, Otherwise, a “0” is given.

- The full-compare units have been used to generate the PWM outputs.

- The PWM signal is high when the output of current PI regulation matches the value of T1CNT and set low when the Timer underflow occurs.

- The switch states are controlled by the ACTR register.
PWM Generation

- As discussed before, the lower switches should always be on and the upper switches should be chopped.
- From the point of implementation on the LF2407, this requires that the ACTR register is reset for each interval.
- Therefore, PWM1, PWM3, and PWM5, which trigger the upper switches, are set as *active low/high* and PWM2, PWM4, and PWM6, which trigger the lower switches are set as *force high*. 
PWM Generation

- The code below illustrates this implementation.

SINE_PWM:

....
....
POINT_B0
  MPY   Ub
  PAC
  ADD   PERIOD,15
POINT_EV
  SACH  CMPR2
....
RET
Reading material

- SPRA494-Implementation of Vector Control for PMSM.PDF

- SPRA588-Implementation of a Speed Field Oriented Control PMSM.PDF
## TI C2000: Portfolio for Embedded Applications

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