Sensorless Control on Super High Speed Motors

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Outline

- Super High Speed Permanent Magnet Synchronous Motors (PMSM)
- Sensorless Control
- Simulation Results
- Conclusion
High Speed PMSM

- Advantages
  - High efficiency
  - Small volume
  - High power density

Challenges of High Speed

- Super high speed (50,000 rpm or higher) makes the system highly dynamic, and requires very fast response from the controller.
- Position sensors are not available at very high speed due to reliability and precision issues.
- Other non electrical challenges, such as bearings, cooling, etc.
Sensorless Control

- Motor control needs feedback information like rotor position and speed, etc.
- Mechanical sensors increases instability and cost of the system
- Sensorless control – no mechanical sensors
  - Simplicity
  - Lower cost
- More important for high speed motors where mechanical sensors are often unavailable
Open Loop Control

- Constant V/f Control
  - No feedback required, therefore do not need sensors.
  - Simple and easy to realize.
  - Robustness is bad because of no feedback. Could lose synchronization because of any wrong settings.
  - Can run the PMSM to a very high speed.

Closed-Loop Control – Field Oriented Control (Vector Control)

Dynamical Equations of
PM Motor in dq Frame

\[ \frac{di_d}{dt} = \frac{1}{L_d}(-R_s i_d + \omega_{me} L_q i_q + u_d) \]
\[ \frac{di_q}{dt} = \frac{1}{L_q}(-R_s i_q - \omega_{me} L_d i_d - \omega_{me} \lambda_{PM} + u_q) \]
\[ \frac{d\omega_m}{dt} = \frac{1}{I}(\tau_M - \tau_L - c \omega_m) \]
\[ \frac{d\theta_m}{dt} = \omega_m \]

where
\[ \tau_M = \frac{3p}{4} i_q \left[ \lambda_{PM} + i_d (L_d - L_q) \right] \]
\[ \omega_{me} = \frac{p}{2} \omega_m \]
Current Control Derivation

\[
\tau_M = \tau_L + I\alpha_m + c\omega_m
\]

\[
\alpha_m = \frac{d\omega_m}{dt}
\]

\[
i_q = \frac{\tau_M}{i_q} = \tau_L + I\alpha_m + c\omega_m
\]

\[
i_q = \frac{\tau_M}{i_q} = \tau_L + I\left(k_p \frac{e_{\omega_m}}{\Delta t}\right) + c\omega_m
\]

\[
i_q^* = i_q + \frac{1}{\tau_M} \left[I\left(k_p \frac{e_{\omega_m}}{\Delta t} - \alpha_m\right) + c\left(k_p e_{\omega_m}\right)\right]
\]

\[
i_q^* = i_q + k_i \frac{e_{\theta_m}}{\Delta t} + \frac{2}{p \tau_M} \left[I\left(k_p \frac{e_{\omega_m} - \alpha_m}{\Delta t}\right) + c\left(k_p e_{\omega_m}\right)\right]
\]
Voltage Control Equations

\[ u_d^* = R_s i_d^* + L_d^* \frac{d i_d^*}{d t} - \omega_{me}^* L_q^* i_q^* \]  \hspace{1cm} (2)

\[ u_q^* = R_s i_q^* + L_q^* \frac{d i_q^*}{d t} + \omega_{me}^* L_d^* i_d^* + \omega_{me}^* \lambda_{PM} \]  \hspace{1cm} (3)
Position Estimation Techniques

- Back EMF
  - The rotating rotor will induce a voltage in the winding, which can be detected and used to estimate the rotor position
  - Suitable for mid-high speed. At low speed, back EMF voltage is too small that the signal to noise ratio is too low.

- Signal injection
  - Inject some voltage or current signals (usually high frequency) into the motor and using correspondent signals to detect rotor position
• The induced voltage is dependent on the rotor speed
• By measuring current and voltage of the stator windings, the back EMF information can be obtained

http://www.acroname.com/robotics/info/articles/back-emf/back-emf.html
Two models, one is for estimation, one is the real model

Every state variable in the first model is observable

Only current and voltages of the real motor model is observable

Compare the two models and adjust the estimation model

Highly dependent on parameter accuracy
State Observer or Kalman Filter

- Dynamic equation of state variables and output equation

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx
\end{align*}
\]

- Use some iteration to approach the real position/speed
Dynamic Equation

- State variables and PMSM dynamic equation

\[
\dot{x} = g(x)
\]

\[
\begin{align*}
\frac{di_d}{dt} &= \frac{u_d}{L} - \frac{i_d}{\tau} + \omega i_q \\
\frac{di_q}{dt} &= \frac{u_q}{L} - \frac{i_q}{\tau} - \omega i_d - \frac{\lambda_{PM}}{L} \omega \\
\frac{d\omega}{dt} &= \frac{p^2 \lambda_{PM}}{J} I_q - \frac{c}{J} \omega - \frac{p}{J} \tau_L \\
\frac{d\theta}{dt} &= \omega \\
\frac{d\tau_L}{dt} &= 0
\end{align*}
\]

\[
\tau = \frac{L}{R}, L_d = L_q = L
\]
System

- Observable variables are d-q currents. Use them as output vector

\[ y = \begin{bmatrix} i_d & i_q \end{bmatrix}^T = Cx \]

With \( x = \begin{bmatrix} i_d & i_q & \omega & \theta & \tau_L \end{bmatrix}^T \)

\[ C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \]
Extended Kalman Filter

- Estimate state variables of next time step, then calculate the error covariance matrix, and also the error of estimation, use them to correct the estimation and update the coefficients

1. Compute state ahead and error covariance ahead
   \[ \hat{x}_{k|k-1} = \hat{x}_{k-1|k-1} + g(\hat{x}_{k-1|k-1})T_e \]
   \[ P_{k|k-1} = F_{k-1}P_{k-1|k-1}F_{k-1}^T + Q_{k-1} \]

2. Compute the Kalman gain.
   \[ K_k = P_{k|k-1}C^T \left( CP_{k|k-1}C^T + R_{k-1} \right)^{-1} \]

3. Update estimate with measurement
   \[ \hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \left( y_k - C\hat{x}_{k|k-1} \right) \]

4. Update the error covariance matrix
   \[ P_{k|k} = \left[ I - K_k C \right] P_{k|k-1} \]

Traditional observer:
\[ \hat{x}_k = \hat{x}_{k-1} + g(\hat{x}_{k-1})T_e + K \left( y - C\hat{x}_{k|k-1} \right) \]

Extended Kalman Filter
Controller
Motor and Drive
Simulation Results

Stroke and speed curves
Conclusions

- Sensorless Control is useful and important for high speed PMSM systems.
- Open loop control can be used for high speed PMSM systems, but it has limitations and drawbacks.
- Closed-loop sensorless vector control is tested through simulation.
- Hardware experiment is underway.
References on Sensorless Control

- Hung-Chi Chen; Wei-Shun Huang; Jhen-Yu Liao; , "PMSM sensorless control with Coordinate Rotation Digital Computer," IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society , vol., no., pp.951-955, 7-10 Nov. 2010