Investigation of saturation impact on an IPMSM saliency-based sensorless control for automotive applications

Journée GDR-SEEDS

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HF signal injection-based sensorless control: Objectives & Challenges
Context : Dedicated application & challenges

- PMSM Sensorless control applied to the EV traction context is aimed at :
  
  ✓ Provide the position/speed information necessary for the Torque vector control in the traction chain
  
  ✓ Establish a digital information redundancy with optimized efficiency/cost/volume compromise
  
  ✓ Ensure system & people safety : guarantee the service continuity when a fault on the position sensor appears
  
- The main challenge is to cover the complete Torque/Speed operating area.
Sensorless techniques for a Permanent Magnet Synchronous Machine

- Low speeds & standstill
  - Anisotropy/saliency-based techniques
    - Pulses injection
    - INFORM method
    - HF signal injection method

- High speeds
Description of the HF injection-based sensorless control system
Structure of the sensorless control system

1. Torque vector control layer (ACL)
2. Sensorless algorithm layer (SAL)
HF signal injection algorithm optimization

\[
\text{Min}(\Delta \theta) = f(x_1, x_2, \ldots, x_n)
\]

\[
\Delta \theta \rightarrow 0
\]

where

\[
a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n (\leq, =, \geq) b_1
\]
\[
a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n (\leq, =, \geq) b_2
\]

\[
\ldots
\]
\[
a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n (\leq, =, \geq) b_m
\]

\[
[x_1, x_2, \ldots, x_n] : \text{Control variables}
\]
\[
a_{ij}, b_i : \text{parameters TBD}
\]

In order to indentify the minimization function elements, the sub-systems need to be detailed.
2.1. High frequency signal injection module

In this module, key control variables are $f_h$ and $V_h$, the frequency and the amplitude of the HF signal.

- $f_h$ et $V_h \in \{x_1, x_2, ..., x_n\}$

For $x_1 = f_h$

- $f_h \leq \frac{f_{pwm}}{10} \Rightarrow f_{pwm} = 10\text{KHz}$
- $f_h \leq f_{cem} \Rightarrow \text{TBD}$
- $f_h \gg f_e \Rightarrow 0\text{Hz} < f_e < 120\text{Hz}$
- $f_h \gg \frac{R_s}{2\pi jL} \Rightarrow f_h \gg \frac{R_s}{2\pi jL}$

It is comprised between 5 to 10 Hz for studied machines.
2.1. High frequency signal injection module

For $x_2 = V_h$

$$V_h \leq V_{\text{ripple}}$$

- For a frequency comprised between 500 and 1000 Hz, the audible noise starts from some dBs, and the noise discrimination zone starts from 80 dB.
In this case, $V_h$ is tuned from 5 to 30 V and the corresponding gain does not exceed 35 dB. For this criterion, the induced noise is then considered acceptable.

- On another hand, $V_h$ should be tuned based on the induced torque ripple $\Rightarrow$ For example
Torque ripple $< 20\%$ Torque reference

$$V_h > V_{DT} = \frac{DT + T_{ON} - T_{OFF}}{T_s} V_{dc}$$

$V_{DT} = 1$ to $2V$ for a Dead-Time $DT = 2\mu s$. 
2.4. Expression of the minimization function

\[ \Delta \theta = \text{Min} \left( f_h, V_h, f_{BP}, f_{lp}, f_{bp} \right) \]

Constraints:

\[ b = [ f_{pwm}, f_e, f_{CEM}, V_{ripple}, V_{DT}, f_h, 2f_h, \gamma_{max}] \]
PMSM saturation impact on sensorless control performances

IPMSMs are good candidates for the VE traction chain Field Oriented Control (FOC)

(+ ) High efficiency and power density
(+ ) Reduced cost and size
(+ ) Saliency ratio
(- ) Magnetic saturation

The magnetic saturation emerges as a twofold phenomenon:

- Simple iron saturation
- Cross-saturation (cross-coupling)
Investigation of iron saturation effects on sensorless feasibility
Magnetic saturation impact on differential IPMSM saliency

- Obviously, d-axis inductance hardly varies as function of d-axis and q-axis currents (20%) whereas q-axis inductance considerably varies mainly as function of q-axis current (60%).

- **Saliency ratio varies by 42%** when Torque target varies from 0 N.m to 100 N.m

⇒ Hence, differential inductance \((L_q - L_d)\) is load-dependent: it decreases with the applied torque: It varies by 42% when Torque target varies from 0 N.m to 100 N.m

⇒ Sensorless feasibility is affected
Experimental evidence of IPMSM saliency behaviour

- The power stage is mainly composed of four different elements:

  - Electrical source: Electrical grid/Battery
  - Machine: PMSM1
  - Converters: 6-leg Inverter
  - Load: Asynchronous load machine

<table>
<thead>
<tr>
<th></th>
<th>Maximum power [KW]</th>
<th>Maximum torque [N.m]</th>
<th>Maximum speed [tr/min]</th>
<th>Ld (pu)</th>
<th>Lq (pu)</th>
<th>Rs (Ω)</th>
<th>Pole pairs (pp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMSM-1</td>
<td>180</td>
<td>250</td>
<td>15000</td>
<td>0.15</td>
<td>0.74</td>
<td>0.043</td>
<td>4</td>
</tr>
</tbody>
</table>

Parameters of the test machine
Investigation of \((d,q)\) HF current loci (Rotating carrier)

Rotating carrier injection

\[
V_{\alpha h} = V_h \left[ \frac{\cos(\omega_h t)}{\sin(\omega_h t)} \right]
\]

\[
I_{d\alpha} = I_f + I_{d\alpha h} = I_f e^{j\theta} - jI_{hp} e^{j\omega_h t} - jI_{hn} e^{(j\omega_h t - 2\theta)}
\]

\[
\begin{align*}
I_{dh} &= \frac{V_h}{\omega_h L_d} \cos(\omega_h t - \theta) \\
I_{qh} &= \frac{V_h}{\omega_h L_q} \sin(\omega_h t - \theta)
\end{align*}
\]

\[
\frac{I_{dh}^2}{\left( \frac{V_h}{\omega_h L_d} \right)^2} + \frac{I_{qh}^2}{\left( \frac{V_h}{\omega_h L_q} \right)^2} = 1
\]

\[
I_{dq h} = I_{hp} e^{(j\omega_h t - \theta)} + I_{hn} e^{(-j\omega_h t + \theta)}
\]
PMSM HF output current: FFT analysis

Position observer input

Torque = 50 N.m
Torque = 75 N.m
Torque = 100 N.m
Torque = 200 N.m

I_{\alpha\beta}

I_{\alpha\beta}

I_{\alpha\beta}

I_{\alpha\beta}

I_m (A)

I_m (A)
The sensorless feasible region can be defined as function of saturation effects limitation => Bounded by $L_{dif}=0$
Investigation of cross-coupling effect on estimation accuracy
Evaluation of cross-saturation impact on estimation accuracy

**Generalized flux model**

\[ \phi_d = f_d(I_d, I_q) = L_d(I_d, I_q) \cdot I_d + \phi_m + \phi_{dq}(I_d, I_q) \]

\[ \phi_q = f_q(I_d, I_q) = L_q(I_d, I_q) \cdot I_q + \phi_{qd}(I_d, I_q) \]

**Suggested flux model**

\[ \phi_d = f_d(I_d, I_q) = L_d(I_d) \cdot I_d + \phi_m + K_{dq} \cdot I_q \]

\[ \phi_q = f_q(I_d, I_q) = L_q(I_q) \cdot I_q + K_{qd} \cdot I_d \]

\[ K_{dq} = \frac{\partial \phi_d}{\partial I_q} \]

\[ K_{qd} = \frac{\partial \phi_q}{\partial I_d} \]
Compensation procedure

Available Data

\[
\begin{aligned}
\phi_d &= \phi_d (I_d, I_q) \\
\phi_q &= \phi_q (I_d, I_q)
\end{aligned}
\]

and

\[
\begin{aligned}
\phi_d &= \phi_d (I_d) \\
\phi_q &= \phi_q (I_q)
\end{aligned}
\]

Off-line algorithm

1. \( \phi_{dq} = \phi_d (I_d, I_q) - \phi_d (I_d) \)
   \( \phi_{qd} = \phi_q (I_d, I_q) - \phi_q (I_q) \)

2. \( k_{dq} = \frac{\phi_{dq}}{I_q} \quad k_{qd} = \frac{\phi_{qd}}{I_d} \)

\[\phi_d = f_d (I_d, I_q) = L_{d(I_d)} I_d + \phi_m + K_{dq} I_q \]
\[\phi_q = f_q (I_d, I_q) = L_{q(I_q)} I_q + K_{qd} I_d \]

**PS: For simplifying reasons, Kdq is considered to be equal to Kqd**

3- Plot a LUT for kdq and induced \( \theta_{sat} \) values

\[
\theta_{sat} = \arctg \left[ \frac{2k_{dq}}{L_d - L_q} \right]
\]
Solution: Refer to the original flux linkage cartography as function of currents \((\text{Model } (2))\)

\[
\begin{align*}
\phi_d &= \phi_d (I_d, I_q) \\
\phi_q &= \phi_q (I_d, I_q)
\end{align*}
\]

\(\text{Model } (2)\)

**Flux linkages measurement (VALEO)**

A and B are two points in \((d, q)\) plane:

\[
\begin{align*}
A(I_d, I_q) \\
B(I_d, -I_q) \implies I_A &= I_B^*
\end{align*}
\]

**Principle:**

1- Impose \(I_d\) and \(I_q\) current references \((A(I_d, I_q))\) and measure the corresponding \(V_d\) and \(V_q\) \((V_{dA} \text{ and } V_{qA})\)

\[
\begin{align*}
V_{dA} &= R_s I_d - \omega \phi_q \\
V_{qA} &= R_s I_q + \omega \phi_d
\end{align*}
\]

2- Impose \(I_d\) and \(-I_q\) current references \((B(I_d, -I_q))\) and measure the corresponding \(V_d\) and \(V_q\) \((V_{dB} \text{ and } V_{qB})\)

\[
\begin{align*}
V_{dB} &= R_s I_d + \omega \phi_q \\
V_{qB} &= -R_s I_q + \omega \phi_d
\end{align*}
\]

\[
\begin{align*}
\frac{1}{2} (V_{dA} - V_{dB}) &= -\omega \phi_q \\
\frac{1}{2} (V_{qA} + V_{qB}) &= \omega \phi_d
\end{align*}
\]
Cross-coupling terms : Predicted position error

- Cross-coupling term $K_{dq}$ is varying mainly as function of $I_q$ which confirms the experimental measurements previously shown.

- Resulting calculated position offset $\theta_{sat}$ also corresponds to the one previously measured on bench.
Position error obtained by experiments

Estimated versus real position. (a) $T=20\,\text{N.m}$, (b) $T=50\,\text{N.m}$, (c) $T=100\,\text{N.m}$, (d) $T=150\,\text{N.m}$

Operating speed : 300 rpm
Conclusion
This paper evaluates the performance and the feasibility of saliency-based sensorless control implemented algorithms along the specified operating range for an automotive application.

It has been highlighted that:

- Iron saturation strongly affects the observer input signal quality. => Sensorless feasibility may be affected in saturated operating mode.

- The estimated position is impacted by a load-dependent phase delay.

Thus, the challenge is first to preserve a proper signal to-noise ratio along the operating area, and then to correctly compensate the angular displacement of the position estimate while implementing the control algorithm.