Rotor position estimation in IPM motor drives based on PWM current harmonics

Adriano Faggion   Silverio Bolognani   Luca Sgarbossa

Electric Drives Laboratory
Department of Electrical Engineering
University of Padova

EDLab

IEEE - IEMDC 2011
International Electric Machines and Drives Conference
Niagara Falls, 15-18 May 2011

EDLab

This presentation refers to the paper:

Adriano Faggion, Silverio Bolognani, and Luca Sgarbossa

”Rotor position estimation in IPM motor drives based on PWM current harmonics”

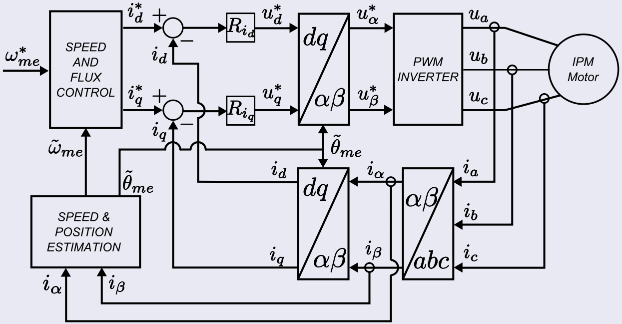
IEEE - IEMDC 2011
International Electric Machines and Drives Conference
Niagara Falls (CANADA), 15-18 May 2011

Outline

High injection method in sensorless technique

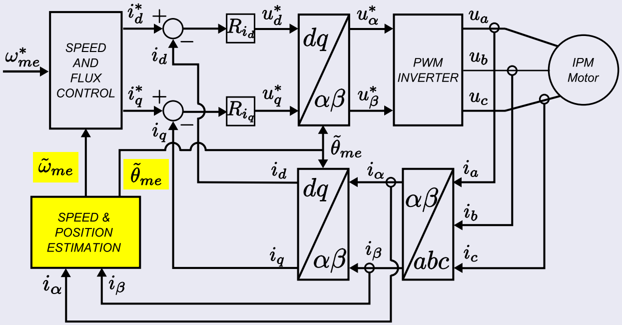
- Nowadays the sensorless position control based on high frequency injected signals is largely studied.
- The method is based on the injection of high frequency sine wave additional voltages, that are added to the fundamental voltages that feed the machine.
- The high frequency signals can be inject in the stationary ($\alpha - \beta$) or in the rotating ($d - q$) reference frame.

Sensorless control drive scheme



A. Faggion er al., "Rotor position estimation in IPM motor drives based on PWM current harmonics", Niagara Falls CANADA

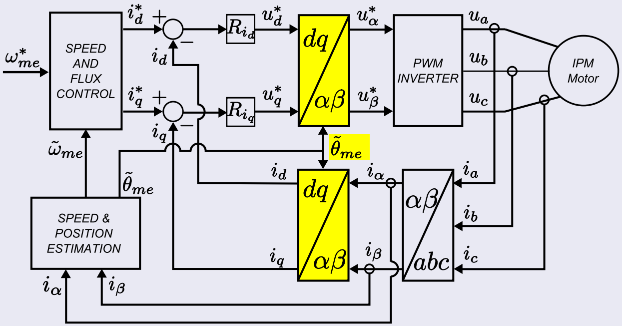
Sensorless control drive scheme



The estimated speed $\tilde{\omega}_{me}$ and position $\tilde{\theta}_{me}$ are delivered by an estimation algorithm.

EDLab

Sensorless control drive scheme



The estimated position $\tilde{\theta}_{me}$ is used in the reference frame transformations.

Fundamental voltages

In the case of three phase motor drive, the fundamental voltages feeding the motor are:

$$u_a^*(t) = U\cos\left(\theta_u\right) \quad (1)$$

$$u_b^*(t) = U\cos\left(\theta_u - \frac{2\pi}{3}\right) \quad (2)$$

$$u_c^*(t) = U\cos\left(\theta_u + \frac{2\pi}{3}\right) \quad (3)$$

where $\theta_u = \tilde{\theta}_{me} + \theta_u^r$

Really, due to the inverter, the actual voltages applied to the motor are the result of the PWM control.

Space vector PWM inverter

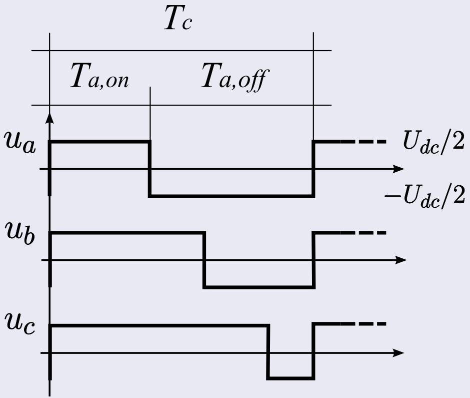
- The voltages, delivered by a space vector PWM inverter, are composed by an infinite sum of sine waves.
- Among this harmonics there are also those around the switching frequency *fc*.
- Then, there is an intrinsic high frequency injection due to the PWM modulation.

Space vector PWM inverter

The idea proposed in this work is the exploitation of the PWM effects in the stator currents for the electrical rotor position estimation.

Single Edge PWM modulation

In the work the single edge PWM modulation with switching period $T_c = 1/f_c$ are taken into account.



Phase *a* voltage frequency analysis

It is possible to derive the expression of the voltage harmonic component at switching frequency f_c of a generic phase voltage $u_{\cdot c}$ applying the Fourier series complex form:

$$u_{\cdot c} = \dot{u}^{+} e^{i\omega_c t} + \dot{u}^{-} e^{-i\omega_c t}$$

with $\dot{u}^{+}$ and $\dot{u}^{-} \in \mathbf{C}$, $\omega_c = 2\pi f_c$

At frequency ω_c there are two voltage vectors that rotate in clockwise and anti–clockwise direction. This is peculiar of the single edge PWM. Symmetrical PWM has not harmonic vectors at frequency ω_c.

Phase *a* voltage frequency analysis

Starting from the phase *a* voltage, it results:

$$\dot{u}_a^+ = \frac{1}{T_c}\int_0^{T_c} u_a(t)e^{-i\omega_c t}dt \quad (4)$$

$$= \frac{1}{T_c}\left[\int_0^{T_{a,on}} \frac{U_{dc}}{2}e^{-i\omega_c t}dt + \int_{T_{a,on}}^{T_c} -\frac{U_{dc}}{2}e^{-i\omega_c t}dt\right] \quad (5)$$

$$= \frac{iU_{dc}}{2\pi}[e^{-i\omega_c T_{a,on}} - 1] \quad (6)$$

and

$$\dot{u}_a^- = conj(\dot{u}_a^+) = -\frac{iU_{dc}}{2\pi}[e^{i\omega_c T_{a,on}} - 1] \quad (7)$$

Phase *a* voltage frequency analysis

$\dot{u}_a^+$ and $\dot{u}_a^-$ can be substituted in the initially equation:

$$u_{a_c} = \frac{iU_{dc}}{2\pi}[e^{-i\omega_c T_{a,on}} - 1]e^{i\omega_c t} - \frac{iU_{dc}}{2\pi}[e^{i\omega_c T_{a,on}} - 1]e^{-i\omega_c t} \quad (8)$$

Finally it results

$$u_{a_c} = \frac{U_{dc}}{\pi}\cos(\omega_c t)\sin(\omega_c T_{a,on}) - \quad (9)$$
$$- \frac{U_{dc}}{\pi}\sin(\omega_c t)\cos(\omega_c T_{a,on}) + \frac{U_{dc}}{\pi}\sin(\omega_c t)$$

with

$$T_{a,on} = \frac{1}{U_{dc}}|u|\cos\theta_u + \frac{1}{2} \quad (10)$$

Phase *a* voltage frequency analysis

Using the previously expression for $T_{a,on}$ and the Bessel function, it results:

$$u_{a_c} = A_0 \sin(\omega_c t) + \sum_{n=1}^{+\infty} (-1)^n A_{2n-1} \cos((2n-1)\theta_u) \cos(\omega_c t) - \quad (11)$$

$$- \sum_{n=1}^{+\infty} A_{2n} \cos(2n\theta_u) \sin(\omega_c t) \quad (12)$$

with

$$A_0 = \frac{U_{dc}}{\pi}\left[J_0\left(\frac{2\pi|u|}{U_{dc}}\right) - \frac{1}{2}\right] \quad (13)$$

$$A_{2n-1} = 2\frac{U_{dc}}{\pi} J_{2n-1}\left(\frac{2\pi|u|}{U_{dc}}\right)$$

$$A_{2n} = 2\frac{U_{dc}}{\pi} J_{2n}\left(\frac{2\pi|u|}{U_{dc}}\right)$$

where J_n denotes the Bessel function of order n.

EDLab

Phases *b* and *c* voltage frequency analysis

Similarly, the phase *b* and *c* high frequency voltages can be computed.

$$
\begin{aligned}
u_{b_c} &= A_0 \sin(\omega_c t) + \sum_{n=1}^{+\infty} (-1)^n A_{2n-1} \cos\left((2n-1)\left(\theta_u - \frac{2\pi}{3}\right)\right) \cos(\omega_c t) - \\
&\quad - \sum_{n=1}^{+\infty} A_{2n} \cos\left(2n\left(\theta_u - \frac{2\pi}{3}\right)\right) \sin(\omega_c t) \qquad (14) \\
u_{c_c} &= A_0 \sin(\omega_c t) + \sum_{n=1}^{+\infty} (-1)^n A_{2n-1} \cos\left((2n-1)\left(\theta_u + \frac{2\pi}{3}\right)\right) \cos(\omega_c t) - \\
&\quad - \sum_{n=1}^{+\infty} A_{2n} \cos\left(2n\left(\theta_u + \frac{2\pi}{3}\right)\right) \sin(\omega_c t)
\end{aligned}
$$

High frequency harmonics of voltages u_α and u_β

Transforming the previously high frequency voltages in the $\alpha\beta$ reference frame, it results:

$$u'_{\alpha c} = \frac{2}{3}\sum_{n=1}^{+\infty}(-1)^n A_{2n-1}\cos(\omega_c t)\cos((2n-1)\theta_u)\left(1-\cos\left((2n-1)\frac{2\pi}{3}\right)\right) + \\ +\frac{2}{3}\sum_{n=1}^{+\infty}(-1)^n A_{2n}\sin(\omega_c t)\cos(2n\theta_u)\left(1-\cos\left(2n\frac{2\pi}{3}\right)\right) \quad (15)$$

$$u'_{\beta c} = \frac{2}{\sqrt{3}}\sum_{n=1}^{+\infty}(-1)^n A_{2n-1}\cos(\omega_c t)\sin((2n-1)\theta_u)\sin\left((2n-1)\frac{2\pi}{3}\right) + \\ +\frac{2}{\sqrt{3}}\sum_{n=1}^{+\infty}(-1)^n A_{2n}\sin(\omega_c t)\sin(2n\theta_u)\sin\left(2n\frac{2\pi}{3}\right) \quad (16)$$

High frequency harmonics of voltages u_α and u_β

From all the harmonics it is possible to take into account only those dependently on the cosine of θ_u:

$$u_{\alpha_c} = -\frac{A_1}{2}\cos(\omega_c t + \theta_u) - \frac{A_1}{2}\cos(-\omega_c t + \theta_u) \qquad (17)$$
$$= -\frac{A_1}{2}\cos(\omega_c t + \tilde{\theta}_{me} + \theta_u^r) - \frac{A_1}{2}\cos(-\omega_c t + \tilde{\theta}_{me} + \theta_u^r)$$

$$u_{\beta_c} = -\frac{A_1}{2}\sin(\omega_c t + \theta_u) - \frac{A_1}{2}\sin(-\omega_c t + \theta_u) \qquad (18)$$
$$= -\frac{A_1}{2}\sin(\omega_c t + \tilde{\theta}_{me} + \theta_u^r) - \frac{A_1}{2}\sin(-\omega_c t + \tilde{\theta}_{me} + \theta_u^r)$$

The voltage vector is given by two rotating vectors at speeds $\omega_c \pm \tilde{\omega}_{me}$.

High frequency harmonics of currents i_{α_c} and i_{β_c}

With these high frequency voltages, the high frequency currents, in the steady–state operation and neglecting the resistance voltage drop, result in:

$$\begin{aligned} i_{\alpha_c} &= -I_0^+ \sin(\omega_c t + \tilde{\theta}_{me} + \theta_u^r) - \\ &- I_1^+ \sin(\omega_c t + \tilde{\theta}_{me} - 2\theta_{me} + \theta_u^r) - \\ &- I_0^- \sin(\omega_c t - \tilde{\theta}_{me} - \theta_u^r) - \\ &- I_1^- \sin(\omega_c t - \tilde{\theta}_{me} + 2\theta_{me} - \theta_u^r) \end{aligned} \tag{19}$$

$$\begin{aligned} i_{\beta_c} &= I_0^+ \cos(\omega_c t + \tilde{\theta}_{me} + \theta_u^r) - \\ &- I_1^+ \cos(\omega_c t + \tilde{\theta}_{me} - 2\theta_{me} + \theta_u^r) - \\ &- I_0^- \cos(\omega_c t - \tilde{\theta}_{me} - \theta_u^r) + \\ &+ I_1^- \cos(\omega_c t - \tilde{\theta}_{me} + 2\theta_{me} - \theta_u^r) \end{aligned} \tag{20}$$

High frequency harmonics of currents i_{α_c} and i_{β_c}

with:

$$I_0^+ = \frac{L_\Sigma}{L_d L_q}\frac{A_1}{2}\frac{1}{\omega_c + \tilde{\omega}_{me}} \qquad I_1^+ = \frac{L_\Delta}{L_d L_q}\frac{A_1}{2}\frac{1}{\omega_c + \tilde{\omega}_{me}}$$

$$I_0^- = \frac{L_\Sigma}{L_d L_q}\frac{A_1}{2}\frac{1}{\omega_c - \tilde{\omega}_{me}} \qquad I_1^- = \frac{L_\Delta}{L_d L_q}\frac{A_1}{2}\frac{1}{\omega_c - \tilde{\omega}_{me}}$$

where L_d and L_q are d– and q–axis inductances at frequency ω_c respectively, $\tilde{\omega}_{me}$ is the estimated speed and

$$L_\Sigma = \frac{L_q + L_d}{2} \qquad L_\Delta = \frac{L_q - L_d}{2} \tag{21}$$

EDLab

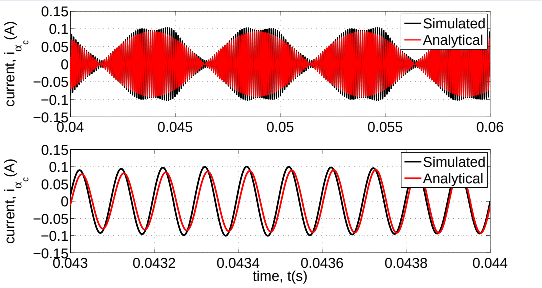
High frequency simulated currents

- Some simulations have been done in order to verify the validity of the high frequency currents i_{α_c} and i_{β_c} expressions.
- In order to extract the i_α and i_β harmonics at f_c, these currents must be measured with a frequency higher than the switching frequency.
- To this purpose the simulated motor currents, filtered with a band pass filter around the switching frequency, are compared with the currents given by previously equations.
- The term A_1 is estimated by a FFT analysis.

EDLab

High frequency simulated currents

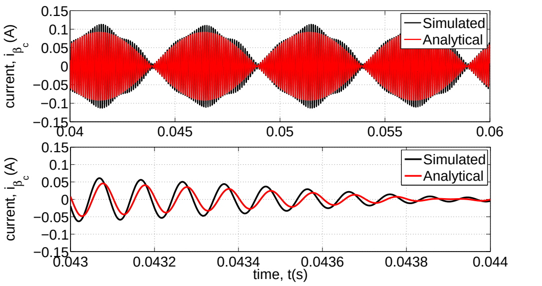
Current i_{α_c} harmonics around the switching frequency



There is a good correspondence between real and reconstructed currents. The discrepancy is due to the other harmonics that are not considered in the mathematic analysis.

High frequency simulated currents

Current i_β harmonics around the switching frequency



Same considerations can be done for the current i_β.

EDLab

Position estimation

For the position estimation purpose, the high frequency currents can be manipulated as follows:

$$\begin{aligned} \epsilon &= i_\alpha \cdot \cos(\omega_c t - \tilde{\theta}_{me} - \theta_u^r) - i_\beta \cdot \sin(\omega_c t - \tilde{\theta}_{me} - \theta_u^r) \\ &= -I_0^+ \sin(2\omega_c t) - I_1^+ \sin(2(\tilde{\theta}_{me} + \theta_u^r - \theta_{me})) - \\ & \quad -I_1^- \sin(2\omega_c t - 2(\tilde{\theta}_{me} + \theta_u^r - \theta_{me})) \end{aligned} \quad (22)$$

Filtering by a low pass filter, the terms at frequency $2\omega_c$ are removed and it results:

$$\epsilon_{LP} = -I_1^+ \sin(2(\tilde{\theta}_{me} + \theta_u^r - \theta_{me})) \quad (23)$$

EDLab

Position estimation

Imposing $\tilde{\theta}'_{me} = \tilde{\theta}_{me} + \theta^r_u$, it results:

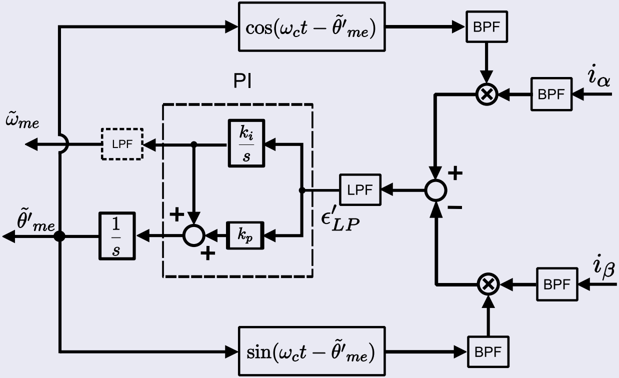
$$\epsilon'_{LP} = -I_1^+ \sin(2\Delta\theta_{me}) \tag{24}$$

where $\Delta\theta_{me} = \tilde{\theta}'_{me} - \theta_{me}$.

- The $sin(2\Delta\theta_{me})$ is equal to zero when also $\Delta\theta_{me}$ is zero, that is when $\tilde{\theta}'_{me}$ is equal to the electrical position θ_{me}.
- An adjustment mechanism can thus correct the estimated position to nullify the error $\Delta\theta_{me}$.
- A PI regulator is used to nullify ϵ'_{LP} and to deliver the estimated position and speed.

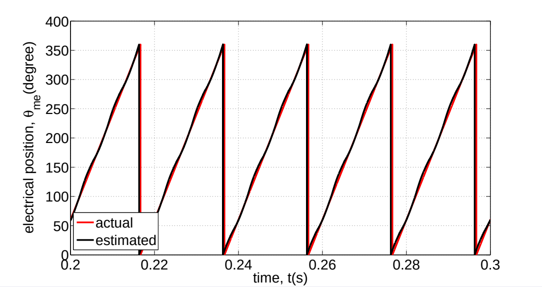
Position estimation

Estimator scheme



Position estimation

Estimated position and actual one (simulation)



A. Faggion er al., "Rotor position estimation in IPM motor drives based on PWM current harmonics", Niagara Falls CANADA

Position estimation

Estimated position and actual one (simulation)

- One can note the good correspondence between the estimated position (black line) and the actual one (red line).
- Simulation confirms the possibility to estimate the rotor position starting from the high frequency stator currents due to the PWM voltage control.
- Discrepancy is due to the other PWM harmonics that are not completely rejected by the filter.

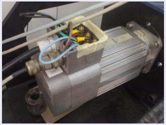
Experimental setup

- Due to the specific and particular innovative strategy used to extract the position information, it is mandatory to validate the proposal with the experimentation.
- Switching frequency has been posed equal to 6.250 kHz.
- An oversampled current measure in a test bench has be implemented and all the samples have been imported in MatLab.

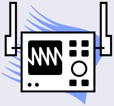
Experimental setup

Switching frequency harmonic currents

1. Currents i_a, i_b is measured and the third i_c is derived.
2. Acquisition and saving with 400 samples per period by means of oscilloscope.
3. Post elaboration with a high pass digital filter of 4^{th} order filter around f_c



IPM motor

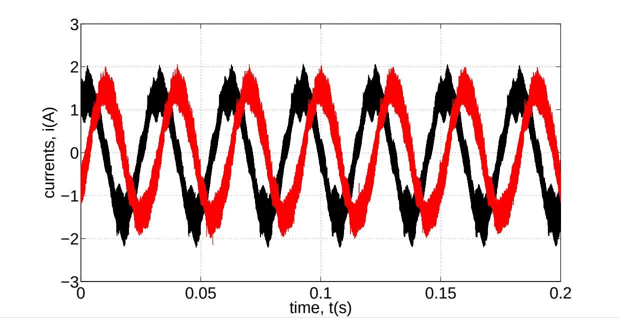


Currents and position measuring and saving by means of oscilloscope

Post elaboration with Simulink and Matlab

Experimental results

Stator currents i_α (black line) and i_β (red line)

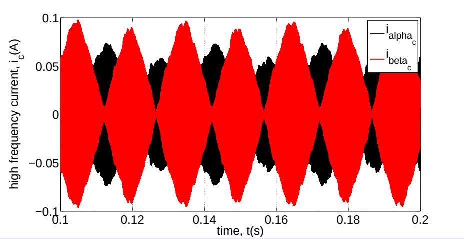


The saved currents are imported in a Simulink model very similar to that used for the simulations.

EDLab

Experimental results

High frequency stator currents i_{α_c} (black line) and i_{β_c} (red line)



High frequency stator currents are obtained filtering the measured by a band pass filter, centered at the switching frequency.

The result is very similar to the expectation proposed by the analysis and the results obtained in the simulation.

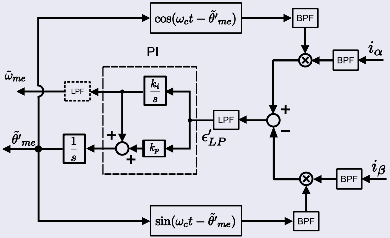
EDLab

Experimental results

Estimation purpose

- The current samples are applied to the estimated scheme used in the simulation.
- The output of the estimator is compared to the actual (measured) quantities.

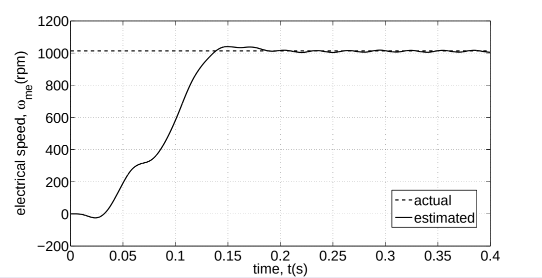
Estimator scheme



EDLab

Experimental results

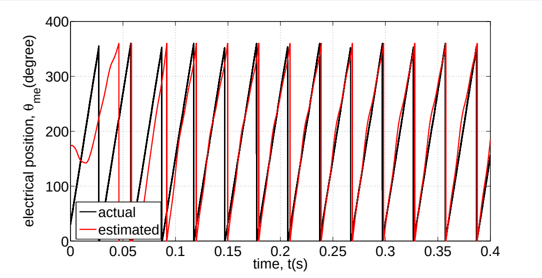
Estimated speed (solid line) and actual one (dashed line)



The estimated speed reaches the actual one after an initially transient. A reduced oscillation is present on the estimated speed: this effect may be due to a DC–BUS oscillation.

Experimental results

Estimated position (red line) and actual one (black line)



- ✓ The estimated position follows the actual one.
- ✓ Test confirms the possibility to extract the position.
- ✓ Oscillations in the estimated speed get oscillations in the estimated position.

EDLab

Conclusions

- Rotor position estimation using PWM intrinsic voltage harmonics injection has been presented.
- At first, the theoretical treatment has been discussed.
- A preliminary theory confirmation has been obtained by estimating the position by means of simulations.
- The position has been estimated with an acceptable precision using a post elaboration of the oversampled motor currents.
- The new estimation technique appears therefore viable, provided that the current oversampling and post elaboration need are solved.
- A full digital implementation of the sensorless drive coming soon.

EDLab

Related Papers by the Authors

S. Bolognani, and A. Faggion,
"*A new proposal of rotor position estimation in ipm motor drives based on pwm current harmonics.*", In Sensorless Control for Electrical Drives (SLED), 2010 First Symposium on, pages 86–92, jul. 2010.

Thank you for the attention.