Hochschule München University of Applied Sciences

Laboratory for Mechatronic and Renewable Energy Systems (LMRES)

Saliency-based rotor position estimation from standstill to high speed

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Introduction

Sensorless rotor position estimation over the full speed range

Field-oriented control needs the rotor angle ϕ_{p}.

⇒ A position sensor adds (i) cost, (ii) error rate, (iii) installation space and cabling.

⇒ **estimate ϕ_{p} from the electrical quantities only.**

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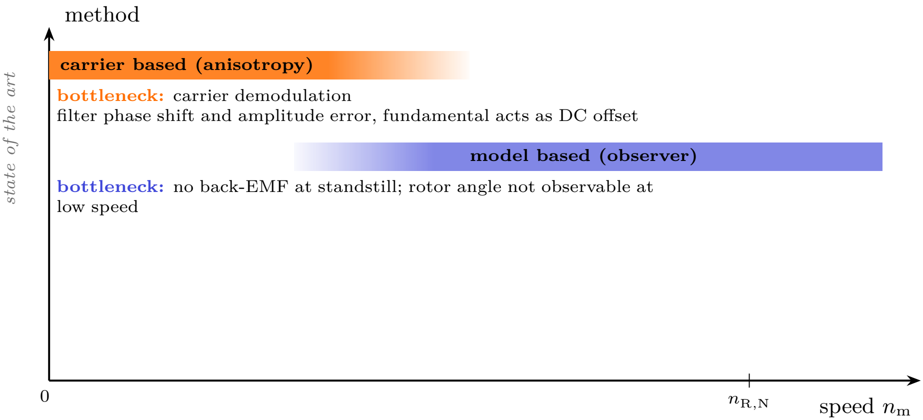

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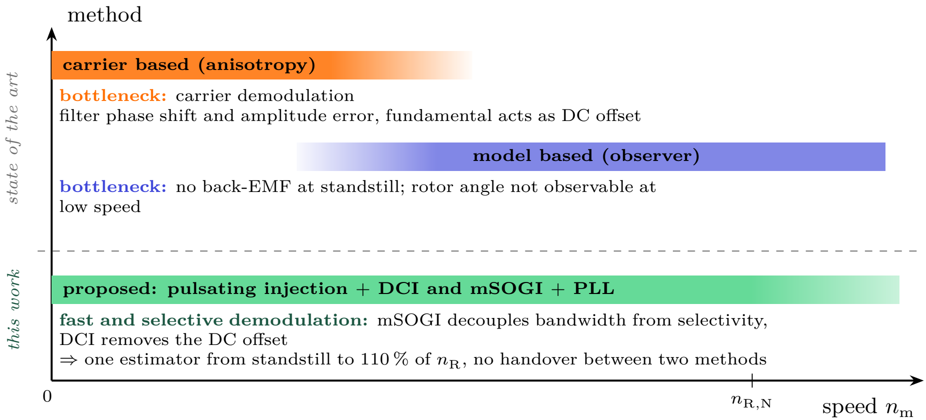

Machine model and anisotropy frame

Where the position information sits

$$\boldsymbol{u}_{\mathrm{s}}^{dq} = \boldsymbol{R}_{\mathrm{s}}^{dq}\boldsymbol{i}_{\mathrm{s}}^{dq} + \omega_{\mathrm{p}}\boldsymbol{L}_{\mathrm{s}}^{dq}\boldsymbol{J}\boldsymbol{i}_{\mathrm{s}}^{dq} + \boldsymbol{L}_{\mathrm{s}}^{dq}\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq} + \frac{\partial\boldsymbol{\psi}_{\mathrm{s}}^{dq}}{\partial\phi_{\mathrm{p}}}\,\omega_{\mathrm{p}}$$

with $\boldsymbol{L}_{\mathrm{s}}^{dq} := \frac{\partial\boldsymbol{\psi}_{\mathrm{s}}^{dq}}{\partial\boldsymbol{i}_{\mathrm{s}}^{dq}} = \begin{bmatrix} L_{\mathrm{s}}^{dd} & L_{\mathrm{s}}^{dq} \\ L_{\mathrm{s}}^{qd} & L_{\mathrm{s}}^{qq} \end{bmatrix}$

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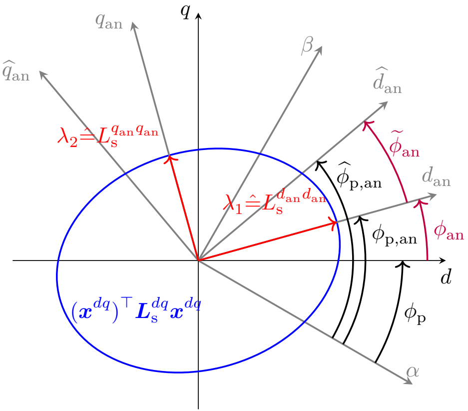
$\boldsymbol{L}_{\mathrm{s}}^{dq}$ is symmetric, hence diagonalizable by a rotation $\phi_{\mathrm{an}} := \phi_{\mathrm{p,an}} - \phi_{\mathrm{p}}$:

$$\boldsymbol{T}_{\mathrm{p}}^{-1}(\phi_{\mathrm{an}})\boldsymbol{L}_{\mathrm{s}}^{dq}\boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{an}}) = \begin{bmatrix} L_{\mathrm{s}}^{d_{\mathrm{an}}d_{\mathrm{an}}} & 0 \\ 0 & L_{\mathrm{s}}^{q_{\mathrm{an}}q_{\mathrm{an}}} \end{bmatrix} = \boldsymbol{L}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}$$



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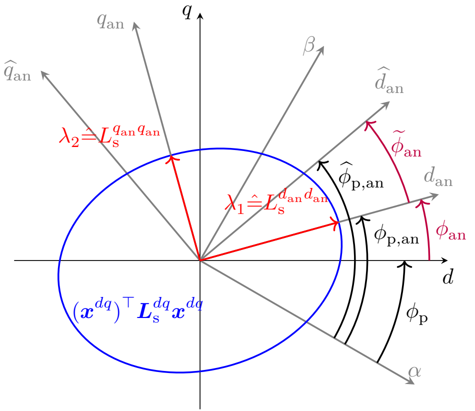


Transformation with $\boldsymbol{T}_{\mathrm{p}}^{-1}(\phi_{\mathrm{an}})$ into the $(d_{\mathrm{an}}, q_{\mathrm{an}})$-frame:

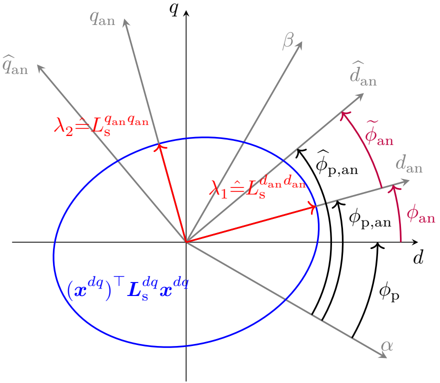
$$\boldsymbol{u}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}} = \boldsymbol{R}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}\boldsymbol{i}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}} + \omega_{\mathrm{p}}\boldsymbol{L}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}\boldsymbol{J}\boldsymbol{i}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}} + \boldsymbol{L}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}} + \left(\underbrace{\boldsymbol{L}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}\boldsymbol{J}\boldsymbol{i}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}\frac{\mathrm{d}}{\mathrm{d}t}\phi_{\mathrm{an}}}_{\to\,0 \text{ for } \phi_{\mathrm{an}}\to\,0} + \frac{\partial\boldsymbol{\psi}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}}{\partial\phi_{\mathrm{p}}}\,\omega_{\mathrm{p}}\right)$$

Pulsating carrier injection

Position information in the carrier current

Carrier voltage injected along the estimated $\widehat{d}_{\mathrm{an}}$-axis ($\omega_{\mathrm{c}} \gg \omega_{\mathrm{p}}$):

$$\boldsymbol{u}_{\mathrm{s,c}}^{d_{\mathrm{an}}q_{\mathrm{an}}} = \underbrace{\widehat{u}_{\mathrm{s,c}} \cos(\omega_{\mathrm{c}} t)}_{=:u_{\mathrm{s,c}}(t)} \begin{pmatrix} \cos(\widetilde{\phi}_{\mathrm{an}}) \\ \sin(\widetilde{\phi}_{\mathrm{an}}) \end{pmatrix}, \quad \widetilde{\phi}_{\mathrm{an}} = \widehat{\phi}_{\mathrm{p,an}} - \phi_{\mathrm{p,an}}$$



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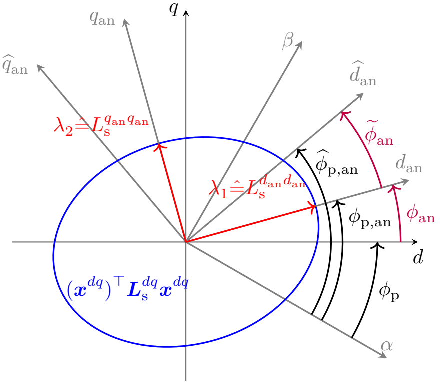
With $\frac{\partial \boldsymbol{\psi}_{\mathrm{s}}^{d_{\mathrm{an}}q_{\mathrm{an}}}}{\partial \phi_{\mathrm{p}}}$ negligible at carrier frequency and $\frac{\mathrm{d}}{\mathrm{d}t}\phi_{\mathrm{an}} \approx 0$:

$$\frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{i}_{\mathrm{s,c}}^{d_{\mathrm{an}}q_{\mathrm{an}}} = \begin{bmatrix} -\frac{R_{\mathrm{s}}^{d_{\mathrm{an}}}}{L_{\mathrm{s}}^{d_{\mathrm{an}}d_{\mathrm{an}}}} & \omega_{\mathrm{p}} \\ -\omega_{\mathrm{p}} & -\frac{R_{\mathrm{s}}^{q_{\mathrm{an}}}}{L_{\mathrm{s}}^{q_{\mathrm{an}}q_{\mathrm{an}}}} \end{bmatrix} \boldsymbol{i}_{\mathrm{s,c}}^{d_{\mathrm{an}}q_{\mathrm{an}}} + \begin{pmatrix} \frac{\cos(\widetilde{\phi}_{\mathrm{an}})}{L_{\mathrm{s}}^{d_{\mathrm{an}}d_{\mathrm{an}}}} \\ \frac{\sin(\widetilde{\phi}_{\mathrm{an}})}{L_{\mathrm{s}}^{q_{\mathrm{an}}q_{\mathrm{an}}}} \end{pmatrix} u_{\mathrm{s,c}}$$



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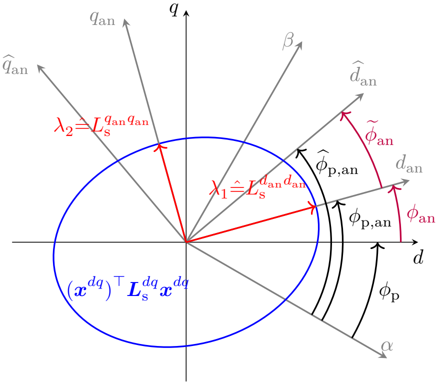
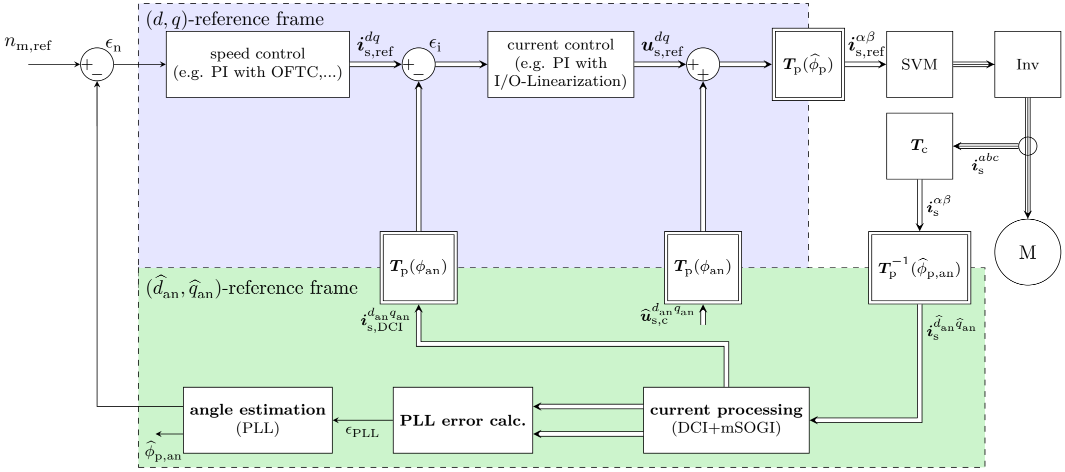


Estimation principle

The carrier q_{an}-component vanishes, if $\widetilde{\phi}_{\mathrm{an}} = 0 \wedge \omega_{\mathrm{p}} = 0$
$\rightarrow$ a PLL can drive $\hat{i}_{\mathrm{s,c}}^{\widehat{q}_{\mathrm{an}}} \rightarrow 0$.

Proposed sensorless control scheme

Overview



Signal model and DCI

What the current sensor actually delivers

Measured current:

$$\boldsymbol{i}_{\mathrm{s}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}} = \underbrace{\boldsymbol{i}_{\mathrm{s,f}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}}}_{\text{DC: feedback for the current control}} + \underbrace{\widehat{\boldsymbol{i}}_{\mathrm{s,c}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}}}_{\text{carrier response: carries } \widetilde{\phi}_{\mathrm{an}}} \left(+ \underbrace{\textstyle\sum_{\nu} \boldsymbol{i}_{\mathrm{s},\nu}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}}}_{\text{higher harmonics}} \right)$$

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Internal model principle: both obey one common model, the fundamental as the **DC** state x_0, the carrier as the rotating state $\boldsymbol{x}_{\mathrm{c}}$:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} x_0 \\ \boldsymbol{x}_{\mathrm{c}} \end{pmatrix} = \omega_{\mathrm{c}}(t)\begin{bmatrix} 0 & \mathbf{0}_2^{\top} \\ \mathbf{0}_2 & \boldsymbol{J} \end{bmatrix}\boldsymbol{x}, \qquad y = (1,1,0)\,\boldsymbol{x}.$$

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The DC part is estimated by a first-order **DC integrator (DCI)**

$$\tfrac{\mathrm{d}}{\mathrm{d}t}\widehat{x}_0 = -\omega_{\mathrm{c}}(t)\, l_0\, \widehat{x}_0 + \omega_{\mathrm{c}}(t)\, l_0\, y_0, \qquad \widehat{y}_0 = \widehat{x}_0,$$

with observer gain $l_0 > 0$ scaled by $\omega_{\mathrm{c}}(t)$.

mSOGI: bandwidth decoupled from selectivity

The core of the demodulator

Carrier current is demodulated by **modified second order generalized integrators (mSOGI)**

$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\boldsymbol{x}}_{\mathrm{c}} = \widehat{\omega}_{\mathrm{c}}\left[\boldsymbol{J}_{\mathrm{c}} - \boldsymbol{l}_{\mathrm{c}}\boldsymbol{c}_{\mathrm{c}}^{\top}\right]\widehat{\boldsymbol{x}}_{\mathrm{c}} + \widehat{\omega}_{\mathrm{c}}\boldsymbol{l}_{\mathrm{c}} y_{\mathrm{c}}, \qquad \widehat{y} = \boldsymbol{c}_{\mathrm{c}}^{\top}\widehat{\boldsymbol{x}}_{\mathrm{c}},$$

with $\widehat{\boldsymbol{x}}_{\mathrm{c}} := (\widehat{y}_{\omega_{\mathrm{c}}}, \widehat{q}_{\omega_{\mathrm{c}}})^{\top}$, $\boldsymbol{J}_{\mathrm{c}} = \boldsymbol{J}$, $\boldsymbol{c}_{\mathrm{c}} = (1,0)^{\top}$ and **two independent gains** $\boldsymbol{l}_{\mathrm{c}} = (k_{\mathrm{c}}, g_{\mathrm{c}})^{\top}$.

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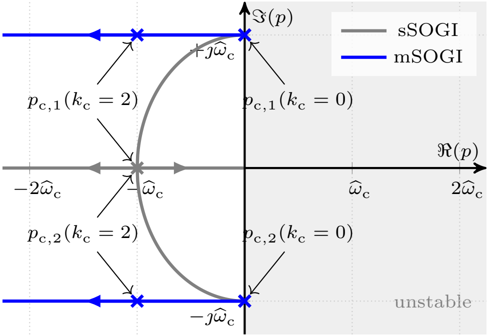

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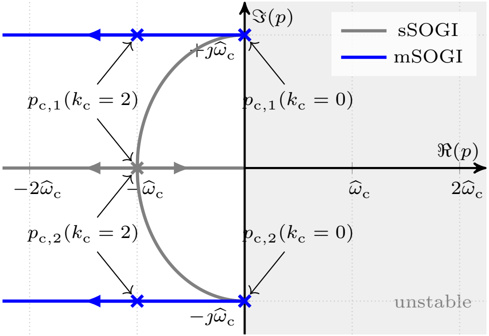

sSOGI

$$p_{\mathrm{c},1/2} = -\frac{\widehat{\omega}_{\mathrm{c}}k_{\mathrm{c}}}{2}\left(1 \pm \sqrt{1-\frac{4}{k_{\mathrm{c}}^2}}\right)$$

mSOGI (for $g_{\mathrm{c}} = -\frac{k_{\mathrm{c}}^2}{4}$)

$$p_{\mathrm{c},1/2} = -\frac{\widehat{\omega}_{\mathrm{c}}k_{\mathrm{c}}}{2} \pm \mathrm{j}\,\widehat{\omega}_{\mathrm{c}}$$

Cascaded DCI+mSOGI

Why a second stage is needed

DCI and mSOGI run in **parallel**, in a **cascaded** structure:

$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\boldsymbol{x}} = \widehat{\omega}_{\mathrm{c}}(t)\begin{bmatrix} \boldsymbol{J}-\boldsymbol{l}\boldsymbol{c}^\top & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{l}\boldsymbol{c}_{\mathrm{c}}^\top & \boldsymbol{J}-\boldsymbol{l}\boldsymbol{c}^\top & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{J}-\boldsymbol{l}\boldsymbol{c}^\top & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{l}\boldsymbol{c}_{\mathrm{c}}^\top & \boldsymbol{J}-\boldsymbol{l}\boldsymbol{c}^\top \end{bmatrix}\widehat{\boldsymbol{x}} + \widehat{\omega}_{\mathrm{c}}(t)\begin{bmatrix} \boldsymbol{l} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{l} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}\boldsymbol{y}, \qquad \widehat{y}_{\mathrm{c}} = \boldsymbol{c}^\top\widehat{\boldsymbol{x}}$$

with the stage state $\widehat{\boldsymbol{x}}_i^\top = (\widehat{x}_0, \widehat{y}_{\omega_{\mathrm{c}}}, \widehat{q}_{\omega_{\mathrm{c}}})$, $\boldsymbol{J} = \begin{bmatrix} 0 & \boldsymbol{0}_2^\top \\ \boldsymbol{0}_2 & \boldsymbol{J}_{\mathrm{c}} \end{bmatrix}$, $\boldsymbol{l}^\top = (l_0,\ k_{\mathrm{c}},\ g_{\mathrm{c}})$, $\boldsymbol{c}^\top = (1,\ 1,\ 0)$, $\boldsymbol{c}_{\mathrm{c}}^\top = (0,\ 1,\ 0)$, $\boldsymbol{y} = \boldsymbol{i}_{\mathrm{s}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}}$.

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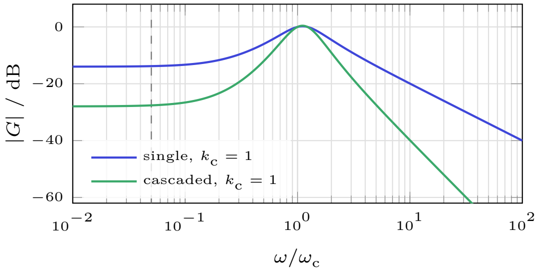
- The second stage sharpens the band-pass selectivity:
- Essential at **high speed**, where **transients** of the fundamental currents would otherwise leak into the PLL error signal.

Does the second stage pay off?

Single vs. cascaded mSOGI, scalar case without DCI

Three demodulators compared, normalized to the carrier ω_c, fundamental at $\omega_c/20$:

- single stage, $k_c = 1$
- cascaded, same $k_c = 1$



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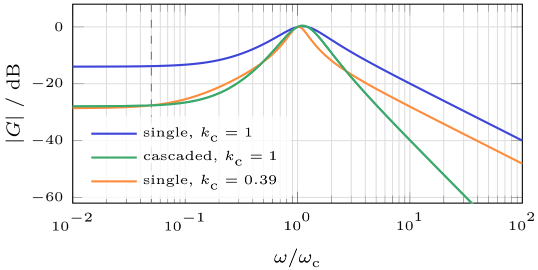

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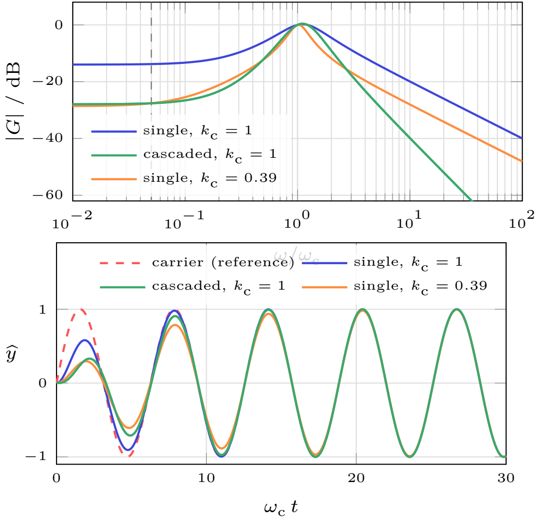
	attenuation at $\omega_c/20$	t_{set} (1 %)
single, $k_c = 1$	-13.8 dB	$8.6/\omega_c$
cascaded, $k_c = 1$	**-27.6 dB**	**$11.8/\omega_c$**
single, $k_c = 0.39$	-27.6 dB	$23.4/\omega_c$

$\Rightarrow$ same selectivity, but **twice as fast**; a single stage never reaches -40 dB/dec.



From carrier currents to angle and speed

Error signal and PLL

Angle error:

$$\begin{pmatrix} \boldsymbol{u}_{\mathrm{s,c}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}} \\ 0 \end{pmatrix} \times \begin{pmatrix} \widehat{\boldsymbol{i}}_{\mathrm{s,c}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \underbrace{\frac{\hat{i}_{\mathrm{s,c}}^{\widehat{q}_{\mathrm{an}}} \widehat{u}_{\mathrm{s,c}}}{2}}_{\mathrm{DC}} + \frac{\hat{i}_{\mathrm{s,c}}^{\widehat{q}_{\mathrm{an}}} \widehat{u}_{\mathrm{s,c}}}{2} \cos(2\omega_{\mathrm{c}} t + 2\varphi_{\mathrm{c}}) \end{pmatrix}$$

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$$\begin{pmatrix} \boldsymbol{u}_{\mathrm{s,c}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}} \\ 0 \end{pmatrix} \times \begin{pmatrix} \widehat{\boldsymbol{i}}_{\mathrm{s,c}}^{\widehat{d}_{\mathrm{an}}\widehat{q}_{\mathrm{an}}} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \underbrace{\frac{\hat{i}_{\mathrm{s,c}}^{\widehat{q}_{\mathrm{an}}}\,\widehat{u}_{\mathrm{s,c}}}{2}}_{\mathrm{DC}} + \frac{\hat{i}_{\mathrm{s,c}}^{\widehat{q}_{\mathrm{an}}}\,\widehat{u}_{\mathrm{s,c}}}{2}\cos(2\omega_{\mathrm{c}}t + 2\varphi_{\mathrm{c}}) \end{pmatrix}$$

The **DC** part is proportional to the unwanted $\widehat{q}_{\mathrm{an}}$-current; its **sign** tells whether the estimated angle is too large or too small.

From carrier currents to angle and speed

Error signal and PLL

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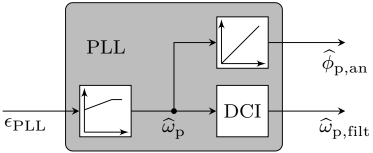
Speed and angle tracking by PLL:

- PI controller with anti-windup maps ϵ_{PLL} to the raw frequency $\widehat{\omega}_{\mathrm{p}}$.
- Pure integration gives $\widehat{\phi}_{\mathrm{p,an}}$, **no additional delay** in the angle path.
- A parallel DCI removes noise and the $2\omega_{\mathrm{c}}$ ripple and yields $\widehat{\omega}_{\mathrm{p,filt}}$ for speed control.



Test case

4 kW reluctance synchronous machine (ABB)

Simulation environment

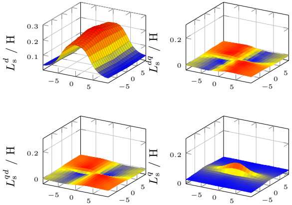
- cascaded, field-oriented control
- space-vector modulator
- switching two-level inverter
- measurement-based nonlinear machine model
- viscous friction load

Estimator and control tuning

- Carrier: $f_c = 2\,\text{kHz}$, $\widehat{u}_{s,c} = 50\,\text{V}$; sampling 8 kHz.
- Current loop $f_{i,\text{cut}} = 50\,\text{Hz}$, speed loop $f_{n,\text{cut}} = 1\,\text{Hz}$, $\xi = 0.7$.
- DCI+mSOGI tuned by pole placement, $\nu = 0.2$.

Motor parameters:

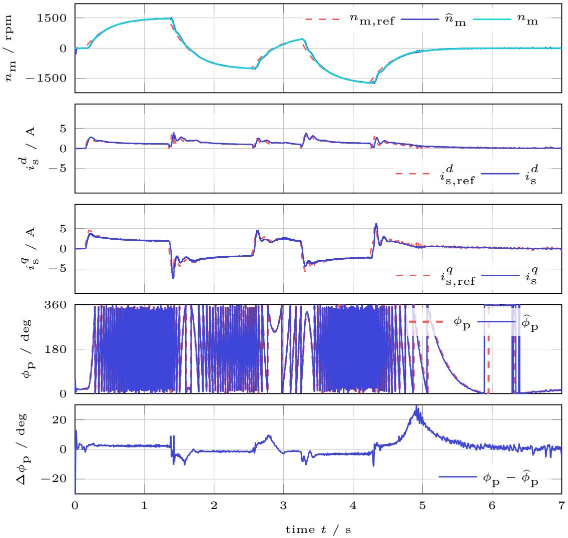
Parameter	Symbol	Value
Rated power	$P_{s,R}$	4 kW
Rated speed	$n_{s,R}$	1500 rpm
Rated torque	$m_{m,R}$	25.5 Nm
Rated current	$I_{s,R}$	9.4 A
Rated voltage	$U_{\text{LtL},R}$	380 V
Rated el. frequency	$f_{s,R}$	100 Hz
Stator resistance	R_s	1.62 Ω
Pole pair number	n_p	2
Switching frequency	f_{pwm}	20 kHz
DC link voltage	u_{DC}	325 V



Inductance maps over the (i_s^d, i_s^q)-plane; $L_s^{dq}, L_s^{qd} \leq 0.011\,\text{H}$.

Simulation results

Speed reversals between −1700 rpm and +1500 rpm



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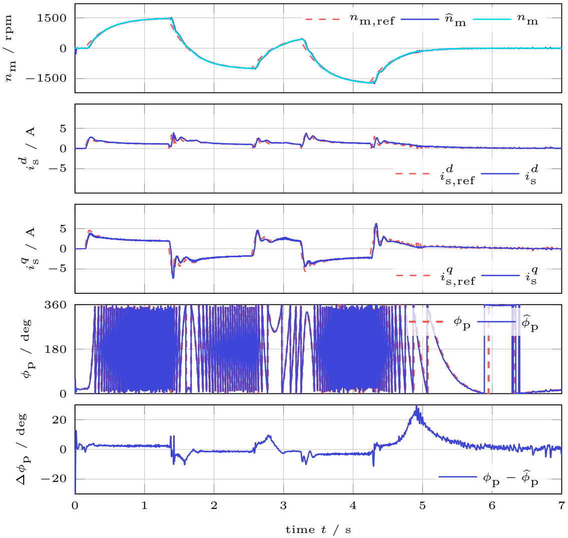

- Reversals up to 110 % of rated speed, including zero-speed crossings.
- Estimated and real speed track the filtered reference with negligible lag.
- $\widehat{\phi}_{\mathrm{p}}$ stays locked to ϕ_{p} at *all* speeds.
- $\Delta\phi_{\mathrm{p}}$ near zero; short excursion at $t \approx 5\,\mathrm{s}$ during a zero-speed crossing, with fast recovery.

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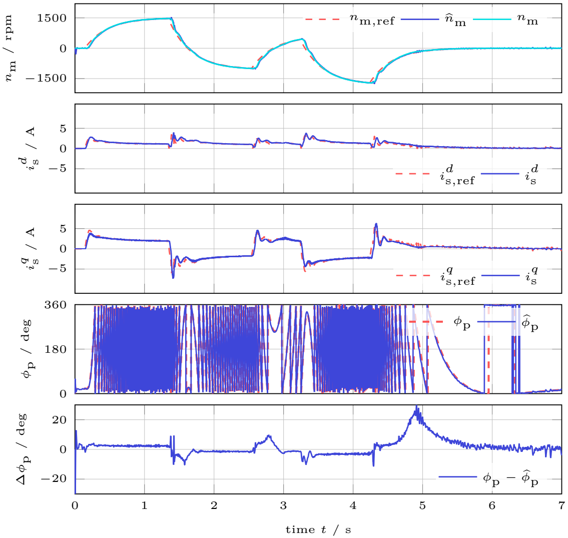

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No handover

One estimator from standstill to above rated speed – no switching between a low- and a high-speed method.

Conclusion & Outlook

Summary & Future Work

Summary

- Saliency-based sensorless scheme for RSM: pulsating injection in the estimated anisotropy frame, demodulation by cascaded **DCI+mSOGI**, tracking by **PLL**.
- **mSOGI**: two independent gains decouple bandwidth from selectivity – fast *and* selective.
- **DCI**: explicitly removes the fundamental current acting as DC offset in the anisotropy frame – the effect that limits classical demodulators at high speed.
- High-fidelity simulation with a measurement-based nonlinear 4 kW RSM model: accurate angle tracking during rapid reversals up to 110 % of rated speed.

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Future Work

- **Experimental validation** on the laboratory drive test bench.
  - Influence of measurement noise, inverter dead time and nonlinearities.
  - Acoustic noise at high speed; operation in the field-weakening region.
  - Parameter sensitivity: temperature drift, magnetic saturation, cross-coupling.

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Thank you for your attention.

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