Robust sensorless flux and position estimation for SynRMs

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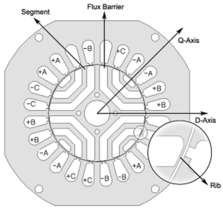
SynRMs

Principle of operation :
The rotor is designed in such a way its magnetic reluctance is lower in one direction, which tends to align with the rotating field produced by stator currents



SynRM (transversal cut) from [Im et al. (2009)]

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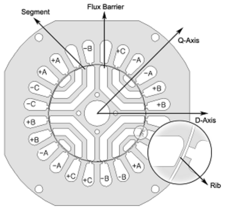
- No expensive permanent magnet ⇒ Cheaper than PMSMs
- Few losses in rotor ⇒ More efficient than IMs



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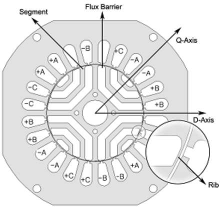
Challenges:

- Sensorless control is more difficult
- Magnetic saturation modeling is paramount for a proper control of the SynRM



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Sensorless control/observation of SynRMs

Sensorless estimation strategies

- basic/extended EMF approach to estimate stator flux, rotor position and speed [Senjyu et al. (2001); Ichikawa et al. (2006)]
- adaptive observers with propotional current control [Tuovinen et al. (2011); Kojima et al. (2020)], or sliding mode current control [Liu et al. (2018); Pavlić et al. (2021)]
- current ripple due to PWM voltage modulation to estimate rotor position [Matsuo and Lipo (1995); Consoli et al. (1999); Capecchi et al. (2001)]

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Contribution : Export stator flux observer designed for PMSMs in [Bernard and Praly (2017, 2018)] to the context of SynRMs allowing to estimate

1. the stator flux, assuming only the resistance, current and voltage known, whatever the magnetic model is;
2. the rotor position fitting at best with the estimated flux, measured current and magnetic model (dynamic optimization)

System model

SynRM model in fixed $\alpha\beta$-frame :

$$\frac{d}{dt}\Psi_{\alpha\beta} = -R\imath_{\alpha\beta} + u_{\alpha\beta} \tag{1}$$

where

- $\Psi_{\alpha\beta} \in \mathbb{R}^2$: total magnetic flux generated by the stator windings
- $\imath_{\alpha\beta} \in \mathbb{R}^2$: current in the stator windings
- $u_{\alpha\beta} \in \mathbb{R}^2$: voltage drop accross the stator windings
- R : stator winding resistance

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Magnetic model in rotor dq-frame $\Psi_{dq}=\mathcal{R}(-\theta)\Psi_{\alpha\beta}$, $\imath_{dq}=\mathcal{R}(-\theta)\imath_{\alpha\beta}$

$$\Psi_{dq} = \begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix} \imath_{dq} + \delta_m(\Psi_{dq}) \tag{2}$$

where

- L_d, L_q : linear inductances
- δ_m : magnetic saturation
- θ : electrical position

Equivalent PMSM-like flux model

Usually : plug (2) into (1) $\Longrightarrow$ electrical + mechanical model

But here : sensorless estimation $\Longrightarrow$ no mechanical signals/parameters

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For $\hat{L} \in \mathbb{R}_{\geq 0}$ arbitrary, we have

$$\Psi_{\alpha\beta} = \hat{L}\imath_{\alpha\beta} + \delta_s(\hat{L}, \Psi_{dq}, \imath_{dq}, \theta)$$

with $\Phi_{eq} := \left\| \delta_s(\hat{L}, \Psi_{dq}, \imath_{dq}, \theta) \right\|$ constant in steady state !

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$\Rightarrow$ Equivalent PMSM model with unknown magnet flux whatever the SynRM magnetic model !

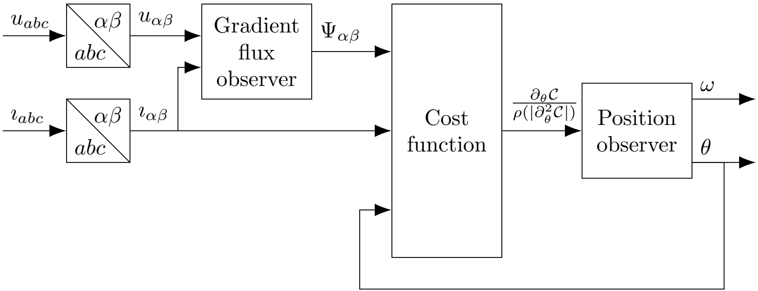
$$\begin{cases} \frac{d}{dt}\Psi_{\alpha\beta} = u_{\alpha\beta} - R\,\imath_{\alpha\beta} \\ \frac{d}{dt}\Phi_{eq} = 0 \end{cases} \quad \text{with} \quad 0 = |\Psi_{\alpha\beta} - \hat{L}\,\imath_{\alpha\beta}|^2 - \Phi_{eq}^2 \tag{3}$$

(Measured signals, Parameter assumed known, Design parameter)

Estimation strategy

Idea :

1. Estimate $(\hat{\Psi}_{\alpha\beta}, \hat{\Phi}_{eq})$ in (3) adapting PMSM observer to unknown magnet flux
2. Estimate θ (and $\dot{\theta}$) matching at best the magnetic model (2) with $(\hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta})$



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Stator flux observer

In steady state ($\imath_{dq}, u_{dq}$ constant)

$$\frac{d}{dt}\Psi_{\alpha\beta} = u_{\alpha\beta} - R\,\imath_{\alpha\beta} \quad , \quad \frac{d}{dt}\Phi_{\text{eq}} = 0 \quad , \quad |\Psi_{\alpha\beta} - \hat{L}\,\imath_{\alpha\beta}|^2 - \Phi_{eq}^2 = 0$$

Theorem

Assume $\Phi_{eq} \neq 0$ *and* $\left|\frac{d}{dt}\theta_{\text{eq}}(t)\right| \geq \underline{\omega} > 0$ *where* $\theta_{\text{eq}} := \arg(\Psi_{\alpha\beta} - \hat{L}\imath_{\alpha\beta})$.

Then, for any $\gamma > 0$, *any* $\hat{\Psi}_{\alpha\beta}(0) \in \mathbb{R}^2$ *and* $\hat{\Phi}(0) > 0$, *any solution of*

$$\begin{cases} \dfrac{d}{dt}\hat{\Psi}_{\alpha\beta} = u_{\alpha\beta} - R\imath_{\alpha\beta} - 2\gamma\,(\hat{\Psi}_{\alpha\beta} - \hat{L}\imath_{\alpha\beta})\left(\left|\hat{\Psi}_{\alpha\beta} - \hat{L}\imath_{\alpha\beta}\right|^2 - \hat{\Phi}^2\right) \\ \dfrac{d}{dt}\hat{\Phi} = \gamma\,\hat{\Phi}\left(\left|\hat{\Psi}_{\alpha\beta} - \hat{L}\imath_{\alpha\beta}\right|^2 - \hat{\Phi}^2\right) \end{cases}$$

verifies

$$\lim_{t\to\infty} |\hat{\Psi}_{\alpha\beta}(t) - \Psi_{\alpha\beta}(t)| = 0 \quad , \quad \lim_{t\to\infty} \hat{\Phi}(t) = |\Phi_{eq}| \ .$$

Stator flux estimated whatever the inductance model $\Rightarrow$ absorbed in Φ_{eq} !

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Position estimator

At each time t, given the flux estimate $\hat{\Psi}_{\alpha\beta}(t)$ and $\imath_{\alpha\beta}(t)$,

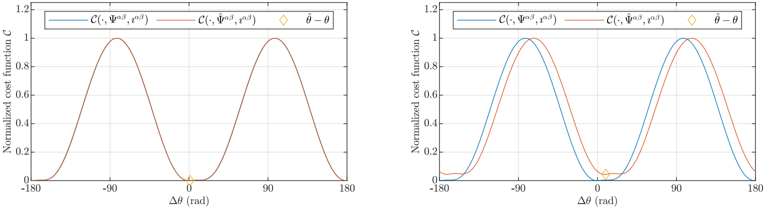
find $\hat{\theta}(t) \in [-\pi, \pi]$ fitting best the magnetic model in *dq*-frame

$$\hat{\theta} = \arg \min_{\theta \in [-\pi,\pi]} \mathcal{C}(\theta, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta}) \ ,$$

where

$$\mathcal{C}(\theta, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta}) = \Big| \underbrace{\hat{\Psi}_{\alpha\beta}}_{Estimate} - \underbrace{\mathcal{R}(\theta) \begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix} \mathcal{R}(-\theta)\imath_{\alpha\beta} - \mathcal{R}(\theta)\delta_m(\hat{\Psi}_{dq}(\theta))}_{Model} \Big|^2$$

Reconstruction of θ modulo π !



(a) Once the flux observer has converged

(b) During the transient of the flux observer

Figure: Shape of $\mathcal{C}(\cdot, \Psi_{\alpha\beta}, \imath_{\alpha\beta})$ in standard conditions.

Dynamic position and speed estimation

Two solutions:

- Minimization of $\mathcal{C}$ at each time step ;
- Or, dynamic observer exploiting $\partial_\theta \mathcal{C}(\theta, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta}) = 0$ and ω slowly varying

$$\begin{cases} \dfrac{d}{dt}\hat{\theta} = \hat{\omega} - \ell k_1 \dfrac{\partial_\theta \mathcal{C}(\hat{\theta}, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta})}{\rho(|\partial_\theta^2 \mathcal{C}(\hat{\theta}, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta})|)} \\ \dfrac{d}{dt}\hat{\omega} = \hat{\mu} - \ell^2 k_2 \dfrac{\partial_\theta \mathcal{C}(\hat{\theta}, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta})}{\rho(|\partial_\theta^2 \mathcal{C}(\hat{\theta}, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta})|)} \\ \dfrac{d}{dt}\hat{\mu} = -\ell^3 k_3 \dfrac{\partial_\theta \mathcal{C}(\hat{\theta}, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta})}{\rho(|\partial_\theta^2 \mathcal{C}(\hat{\theta}, \hat{\Psi}_{\alpha\beta}, \imath_{\alpha\beta})|)} \end{cases}$$

where

- $\rho : \mathbb{R}_{\geq 0} \to \mathbb{R}_{>0}$ regularization map (for instance $\rho(s) = \sqrt{\epsilon^2 + s^2}$, with $\epsilon > 0$)
- $K = (k_1, k_2, k_3)$ such that $\begin{pmatrix} -k_1 & 1 & 0 \\ -k_2 & 0 & 1 \\ -k_3 & 0 & 0 \end{pmatrix}$ Hurwitz,
- $\ell > 0$ picked sufficiently large.

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Experimental results

Observer implemented in Rapid-Prototyping system (from dSpace®), which controls the inverter bridge of a 3kW – 400V industrial drive (Schneider Electric ATV71)

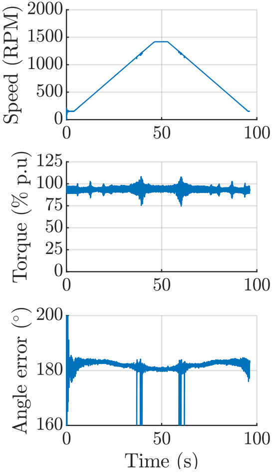
SynRM parameters (magnetic saturation identified in [Combes et al. (2017)])

Rated power	750 W
Rated rotor speed	1500RPM
Rated torque	4.8 N.m
Rated current	2.1 A RMS
Rated voltage	400 V RMS pp
Rated frequency	50 Hz

J	5e-3 $\mathrm{kg.m}^2$
n_p	2
R	6.5 Ω
L_d	590 mH
L_q	584 mH

ψ_{d1}	1.278 Wb
ψ_{d2}	0.947 Wb
ψ_{d3}	0.810 Wb
ψ_{q1}	0.033 Wb
ψ_{q2}	0.148 Wb
ψ_{x1}	– Wb
ψ_{x2}	– Wb

Experimental results



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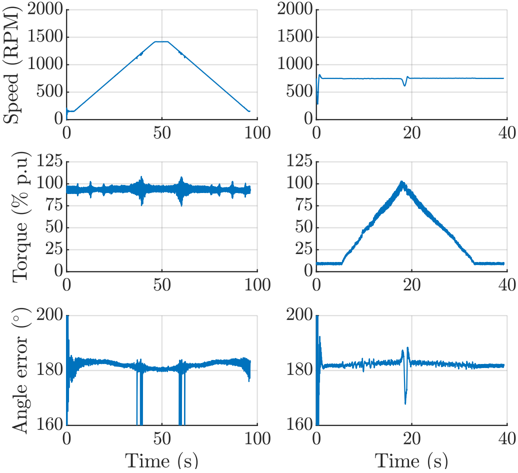

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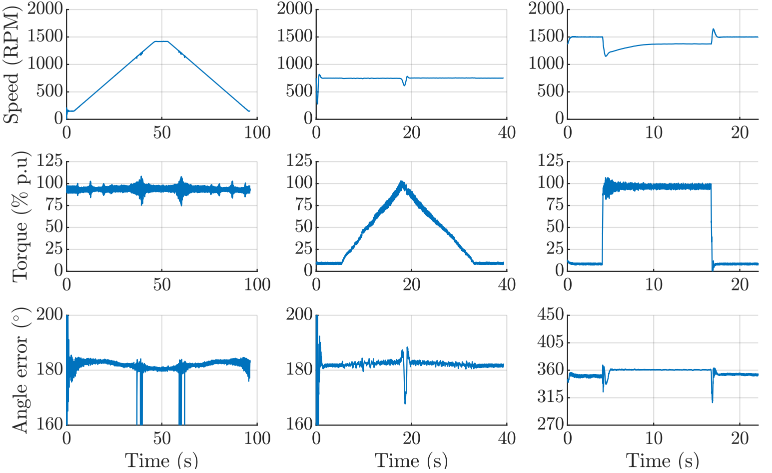

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Conclusion and perspectives

Results :

- observer of stator flux for SynRM without knowing its magnetic model
- dynamic minimization algorithm for estimation of rotor position and speed from flux estimate and magnetic model

Future potentialities :

- improve dynamic behavior of position estimator through better tuning or minimization algorithm (taking into account the non-convexity of cost function)
- use this observer for sensorless control

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