Aalto University
School of Electrical
Engineering

Lecture 11: Sensorless Synchronous Motor Drives

ELEC-E8402 Control of Electric Drives and Power Converters

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Learning Outcomes

After this lecture and exercises you will be able to:

- Explain the voltage-model estimator
- Explain the basic principles of high-frequency signal-injection methods

Rotor-Position Estimation Methods

- Fundamental-excitation-based methods[1]
  - Rely on the mathematical model of the motor
  - Voltage model, observers
  - Sensitive to parameter errors at low speeds
  - Risk of unstable regions also at high speeds if the gains are not properly chosen
- High-frequency signal-injection methods[2,3]
  - Aim to enable sensorless operation at very low speeds
  - Rely on magnetic saliency, $L_\mathrm{d} \neq L_\mathrm{q}$ is necessary
  - Pulsating or rotating excitation signal
  - Dynamic performance may be poor
  - Cause additional losses and noise
  - Often combined with a fundamental-excitation-based method

[1] Jones and Lang, "A state observer for the permanent-magnet synchronous motor," *IEEE Trans. Ind. Electron.*, 1989.

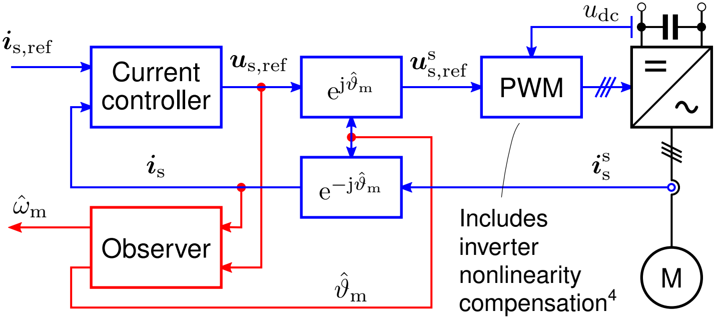
[2] Corley and Lorenz, "Rotor position and velocity estimation for a salient-pole permanent magnet synchronous machine at standstill and high speeds," *IEEE Trans. Ind. Appl.*, 1998.

[3] Ha, Kang, and Sul, "Position-controlled synchronous reluctance motor without rotational transducer," *IEEE Trans. Ind. Appl.*, 1999.

Speed-Adaptive Observer

Observer With High-Frequency Signal Injection

Typical Sensorless Control System



- Reference calculation remains the same as in sensored drives
- Observer could alternatively be implemented in stator coordinates

[4] Holtz, "Pulsewidth modulation for electronic power conversion," *Proc. IEEE*, 1994.

Voltage Model in Stator Coordinates

- Stator flux estimator

$$\frac{\mathrm{d}\hat{\boldsymbol{\psi}}_\mathrm{s}^\mathrm{s}}{\mathrm{d}t} = \boldsymbol{u}_\mathrm{s}^\mathrm{s} - \hat{R}_\mathrm{s}\boldsymbol{i}_\mathrm{s}^\mathrm{s} \quad \Rightarrow$$

$$\hat{\boldsymbol{\psi}}_\mathrm{s}^\mathrm{s} = \int (\boldsymbol{u}_\mathrm{s}^\mathrm{s} - \hat{R}_\mathrm{s}\boldsymbol{i}_\mathrm{s}^\mathrm{s})\mathrm{d}t$$

- Flux estimate

$$\hat{\boldsymbol{\psi}}_\mathrm{s}^\mathrm{s} = \hat{\psi}_\alpha + \mathrm{j}\hat{\psi}_\beta = \hat{\psi}_\mathrm{s}\mathrm{e}^{\mathrm{j}\hat{\vartheta}}$$

- Flux angle estimate

$$\hat{\vartheta} = \text{atan2}\left(\hat{\psi}_\beta, \hat{\psi}_\alpha\right)$$

- Rotor speed in steady state

$$\hat{\omega}_\mathrm{m} = \frac{\mathrm{d}\hat{\vartheta}}{\mathrm{d}t}$$

- Rotor angle $\hat{\vartheta}_\mathrm{m}$ should still be solved from flux equations

Properties of the Voltage Model

- Estimation-error dynamics are marginally stable (pure integration)
- Flux estimate will drift away from the origin due to any offsets in measurements
- Very sensitive to $\hat{R}_{\mathrm{s}}$ and inverter nonlinearities at low speeds
- Good accuracy at higher speeds despite the parameter errors (but pure integration has been remedied)
- Can be improved with suitable feedback $\Rightarrow$ observer
- Can be implemented in estimated rotor coordinates

Real-Time Simulation of Motor Equations

- State estimator in estimated rotor coordinates

$$\frac{\mathrm{d}\hat{\boldsymbol{\psi}}_\mathrm{s}}{\mathrm{d}t} = \boldsymbol{u}_\mathrm{s} - \hat{R}_\mathrm{s}\hat{\boldsymbol{i}}_\mathrm{s} - \mathrm{j}\hat{\omega}_\mathrm{m}\hat{\boldsymbol{\psi}}_\mathrm{s}$$

where the current estimate is

$$\hat{\boldsymbol{i}}_\mathrm{s} = \hat{i}_\mathrm{d} + \mathrm{j}\hat{i}_\mathrm{q}$$

with the components

$$\hat{i}_\mathrm{d} = (\hat{\psi}_\mathrm{d} - \hat{\psi}_\mathrm{F})/\hat{L}_\mathrm{d}$$
$$\hat{i}_\mathrm{q} = \hat{\psi}_\mathrm{q}/\hat{L}_\mathrm{q}$$

- Rotor position estimator

$$\frac{\mathrm{d}\hat{\vartheta}_\mathrm{m}}{\mathrm{d}t} = \hat{\omega}_\mathrm{m}$$

- How to obtain the speed estimate?
- Could we improve this open-loop flux estimator?

Speed-Adaptive Observer

- State observer

$$\frac{\mathrm{d}\hat{\boldsymbol{\psi}}_\mathrm{s}}{\mathrm{d}t} = \boldsymbol{u}_\mathrm{s} - \hat{R}_\mathrm{s}\hat{\boldsymbol{i}}_\mathrm{s} - \mathrm{j}\hat{\omega}_\mathrm{m}\hat{\boldsymbol{\psi}}_\mathrm{s} + \boldsymbol{k}_1(i_\mathrm{d} - \hat{i}_\mathrm{d}) + \boldsymbol{k}_2(i_\mathrm{q} - \hat{i}_\mathrm{q})$$

  where the current estimate is

$$\hat{\boldsymbol{i}}_\mathrm{s} = \hat{i}_\mathrm{d} + \mathrm{j}\hat{i}_\mathrm{q}$$

  with the components

$$\hat{i}_\mathrm{d} = (\hat{\psi}_\mathrm{d} - \hat{\psi}_\mathrm{F})/\hat{L}_\mathrm{d}$$
$$\hat{i}_\mathrm{q} = \hat{\psi}_\mathrm{q}/\hat{L}_\mathrm{q}$$

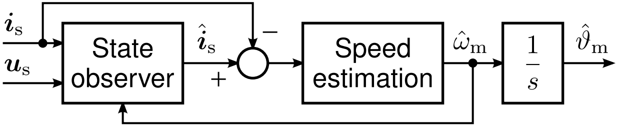
- Rotor position estimator

$$\frac{\mathrm{d}\hat{\vartheta}_\mathrm{m}}{\mathrm{d}t} = \hat{\omega}_\mathrm{m}$$

- Speed estimation

$$\hat{\omega}_\mathrm{m} = k_\mathrm{p}(i_\mathrm{q} - \hat{i}_\mathrm{q}) + k_\mathrm{i}\int(i_\mathrm{q} - \hat{i}_\mathrm{q})\mathrm{d}t$$

  drives $i_\mathrm{q} - \hat{i}_\mathrm{q}$ to zero
- Also the d-component could be used for speed estimation



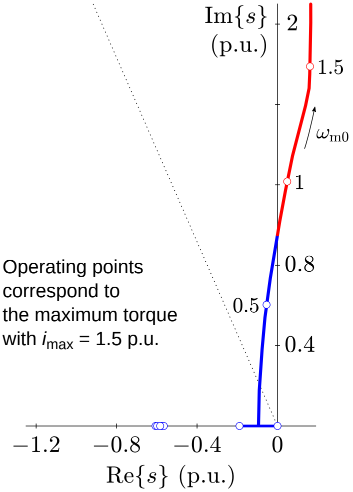
- Constant observer gains $\boldsymbol{k}_1 = g\hat{L}_\mathrm{d}$ and $\boldsymbol{k}_2 = g\hat{L}_\mathrm{q}$ work quite well (typically $g = 2\pi \cdot 15 \ldots 30$ rad/s can be chosen)[5]
- However, interaction between the state observer and the speed estimation may lead to unstable regions[6]
- Stabilizing observer gains $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ decouple two subsystems and enable pole placement
- 6.7-kW SyRM is used as example in the following

[5] Capecchi, Guglielmi, *et al.*, "Position-sensorless control of the transverse-laminated synchronous reluctance motor," *IEEE Trans. Ind. Appl.*, 2001.

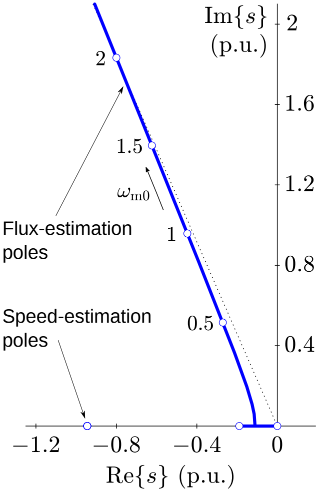
[6] Hinkkanen, Saarakkala, *et al.*, "Observers for sensorless synchronous motor drives: Framework for design and analysis," *IEEE Trans. Ind. Appl.*, 2018.

Observer Poles at the Maximum Torque

Constant observer gain[5]

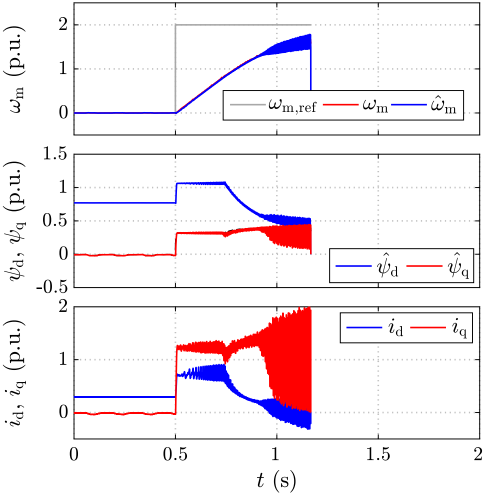


Stabilizing observer gain[6]

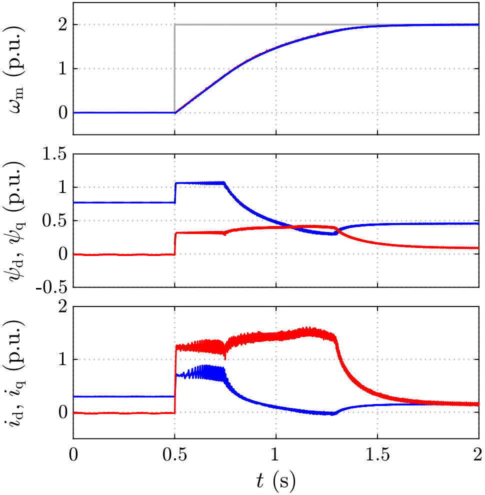


Experimental Results: Acceleration at the Maximum Torque

Constant observer gain[5]



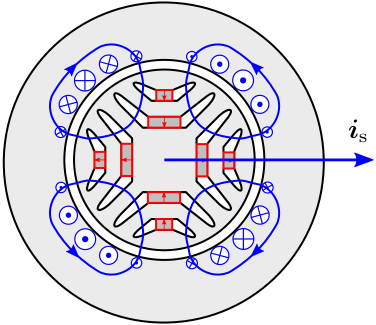
Stabilizing observer gain[6]

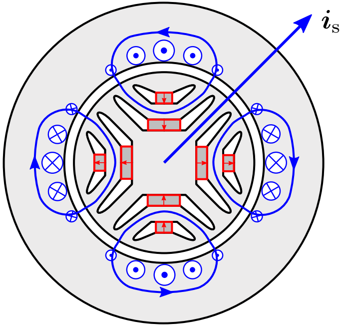


Speed-Adaptive Observer

Observer With High-Frequency Signal Injection

Signal Injection Utilizes the Magnetic Saliency





$$\boldsymbol{i}_\mathrm{s} = i_\mathrm{d} + \mathrm{j}0$$

$$\boldsymbol{\psi}_\mathrm{s} = L_\mathrm{d} i_\mathrm{d} + \psi_\mathrm{F}$$

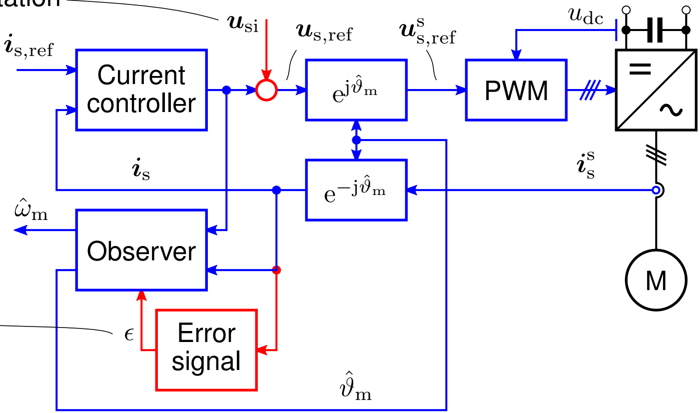
$$\boldsymbol{i}_\mathrm{s} = 0 + \mathrm{j} i_\mathrm{q}$$

$$\boldsymbol{\psi}_\mathrm{s} = \mathrm{j} L_\mathrm{q} i_\mathrm{q} + \psi_\mathrm{F}$$

Sensorless Control Augmented With Signal Injection[7]

High-frequency voltage excitation (typically 0.2. . . 2 kHz, enabled only at low speeds)

Error signal extracted from the high-frequency current response



[7] Piippo, Hinkkanen, and Luomi, "Analysis of an adaptive observer for sensorless control of interior permanent magnet synchronous motors," *IEEE Trans. Ind. Appl.*, 2008.

Position Estimation Error

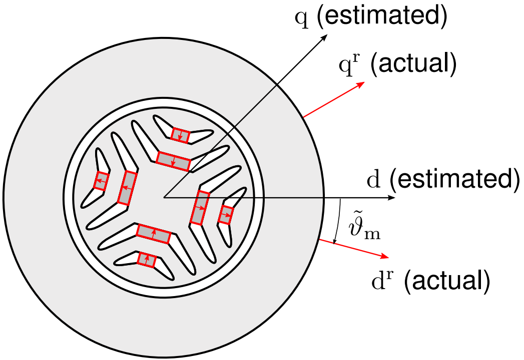
- Controller operates in estimated rotor coordinates (no superscript)
- Actual rotor coordinates are marked with the superscript r
- Some estimation error exists

$$\tilde{\vartheta}_\mathrm{m} = \vartheta_\mathrm{m} - \hat{\vartheta}_\mathrm{m}$$

- This leads to control errors

$$\boldsymbol{i}_\mathrm{s}^\mathrm{r} = \boldsymbol{i}_\mathrm{s}\,\mathrm{e}^{-\mathrm{j}\tilde{\vartheta}_\mathrm{m}}$$

$$\boldsymbol{\psi}_\mathrm{s}^\mathrm{r} = \boldsymbol{\psi}_\mathrm{s}\,\mathrm{e}^{-\mathrm{j}\tilde{\vartheta}_\mathrm{m}}$$



Excitation Voltage and Resulting Current Response

- Subscript i refers to injected high-frequency signals
- High-frequency excitation

$$\boldsymbol{u}_{\mathrm{si}} = u_{\mathrm{i}} \cos(\omega_{\mathrm{i}} t)$$

injected on the d-axis

- Resulting stator flux linkage in estimated rotor coordinates

$$\boldsymbol{\psi}_{\mathrm{si}} = \int \boldsymbol{u}_{\mathrm{si}} \mathrm{d}t = \frac{u_{\mathrm{i}}}{\omega_{\mathrm{i}}} \sin(\omega_{\mathrm{i}} t)$$

assuming $R_{\mathrm{s}} = 0$ and $\omega_{\mathrm{m}} = 0$

- Stator flux linkage in rotor coordinates

$$\begin{aligned} \boldsymbol{\psi}_{\mathrm{si}}^{\mathrm{r}} &= \psi_{\mathrm{di}}^{\mathrm{r}} + \mathrm{j}\psi_{\mathrm{qi}}^{\mathrm{r}} = \boldsymbol{\psi}_{\mathrm{si}}\, \mathrm{e}^{-\mathrm{j}\tilde{\vartheta}_{\mathrm{m}}} \\ &= \frac{u_{\mathrm{i}}}{\omega_{\mathrm{i}}} \sin(\omega_{\mathrm{i}} t) \left(\cos\tilde{\vartheta}_{\mathrm{m}} - \mathrm{j}\sin\tilde{\vartheta}_{\mathrm{m}}\right) \end{aligned}$$

- Resulting high-frequency current response in estimated rotor coordinates

$$\begin{aligned} \boldsymbol{i}_{\mathrm{si}} &= i_{\mathrm{di}} + \mathrm{j} i_{\mathrm{qi}} = \boldsymbol{i}_{\mathrm{si}}^{\mathrm{r}} \mathrm{e}^{\mathrm{j}\tilde{\vartheta}_{\mathrm{m}}} \\ &= \left(\frac{\psi_{\mathrm{di}}^{\mathrm{r}}}{L_{\mathrm{d}}} + \mathrm{j}\frac{\psi_{\mathrm{qi}}^{\mathrm{r}}}{L_{\mathrm{q}}}\right) \left(\cos\tilde{\vartheta}_{\mathrm{m}} + \mathrm{j}\sin\tilde{\vartheta}_{\mathrm{m}}\right) \end{aligned}$$

where $\psi_{\mathrm{di}}^{\mathrm{r}}$ and $\psi_{\mathrm{qi}}^{\mathrm{r}}$ are obtained from the previous equation

Note that ψ_{F} does not affect the high-frequency current response since it is constant.

- Component in the estimated q-direction

$$i_{\mathrm{qi}} = \frac{u_{\mathrm{i}}}{2\omega_{\mathrm{i}}} \frac{L_{\mathrm{q}} - L_{\mathrm{d}}}{L_{\mathrm{d}} L_{\mathrm{q}}} \sin(\omega_{\mathrm{i}} t) \sin(2\tilde{\vartheta}_{\mathrm{m}})$$

is an amplitude modulation of the carrier by the envelope $\sin(2\tilde{\vartheta}_{\mathrm{m}})$

- Demodulation

$$i_{\mathrm{qi}} \sin(\omega_{\mathrm{i}} t) = \frac{u_{\mathrm{i}}}{4\omega_{\mathrm{i}}} \frac{L_{\mathrm{q}} - L_{\mathrm{d}}}{L_{\mathrm{d}} L_{\mathrm{q}}} [1 - \sin(2\omega_{\mathrm{i}} t)] \sin(2\tilde{\vartheta}_{\mathrm{m}})$$

- Low-pass filtering

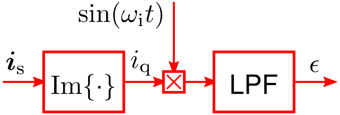
$$\epsilon = \text{LPF}\{i_{\mathrm{qi}} \sin(\omega_{\mathrm{i}} t)\} = \frac{u_{\mathrm{i}}}{4\omega_{\mathrm{i}}} \frac{L_{\mathrm{q}} - L_{\mathrm{d}}}{L_{\mathrm{d}} L_{\mathrm{q}}} \sin(2\tilde{\vartheta}_{\mathrm{m}})$$

- Error signal ϵ is roughly proportional to the position estimation error $\tilde{\vartheta}_{\mathrm{m}}$

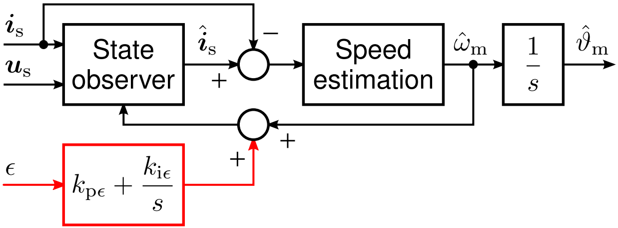
Observer Augmented With Signal Injection

$$\epsilon = \text{LPF}\{i_\mathrm{q}\sin(\omega_\mathrm{i}t)\} \approx \frac{u_\mathrm{i}}{2\omega_\mathrm{i}}\frac{L_\mathrm{q}-L_\mathrm{d}}{L_\mathrm{d}L_\mathrm{q}}\tilde{\vartheta}_\mathrm{m}$$

Error-signal calculation (delay and cross-saturation compensations are omitted in the figure for simplicity)

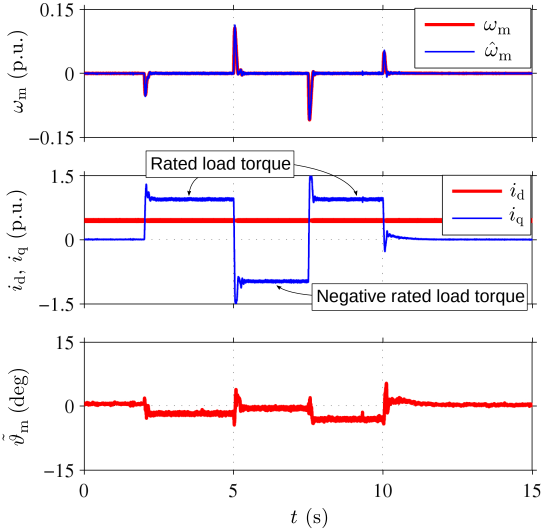


Observer augmented with error signal



Experimental Results: Torque Steps at Zero Speed[8]

- 6.7-kW SyRM drive
- Sustained zero-speed operation (under load torque) possible due to signal injection



[8] Tuovinen and Hinkkanen, "Adaptive full-order observer with high-frequency signal injection for synchronous reluctance motor drives," *IEEE J. Emerg. Sel. Topics Power Electron.*, 2014.

Sensorless Control: Problems and Properties

- Sources of errors in the position estimation
  - Parameter errors: $\hat{R}_\mathrm{s}$ is important at low speeds
  - Accuracy of the stator voltage (inverter nonlinearities)
  - Cross-saturation causes position error in signal injection
- Sustained operation at zero speed (under the load torque) is not possible without signal injection
- Most demanding applications still need a speed or position sensor

Other Control Challenges

- High saliency ratio and low (or zero) PM flux
- High stator frequency, increasing sensitivity to
  - Time delays
  - Discretization
- Parameter variations and inaccuracies
  - Magnetic saturation, core losses
  - Stator resistance and PM flux (temperature)
  - Skin effect (in form-wounded stator windings)
- Identification of the motor parameters
  - Self-commissioning during the drive start-up
  - Finite-element analysis?
  - Role of machine learning in the future?