Lecture 6: Sensorless Control

ELEC-E8402 Control of Electric Drives and Power Converters (5 ECTS)

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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
  - Voltage model, reduced-order observer, or full-order observer
  - Rely on the mathematical model of the motor
  - Sensitive to parameter errors at low speeds
- Signal-injection methods
  - Pulsating excitation signal in estimated rotor coordinates (or rotating excitation signal in stator coordinates)
  - Dynamic performance may be poor
  - Cause additional losses and noise
- Combined methods

A PM-SyRM will be used as an example motor in this lecture, but methods are quite similar for other AC motors as well.

Outline

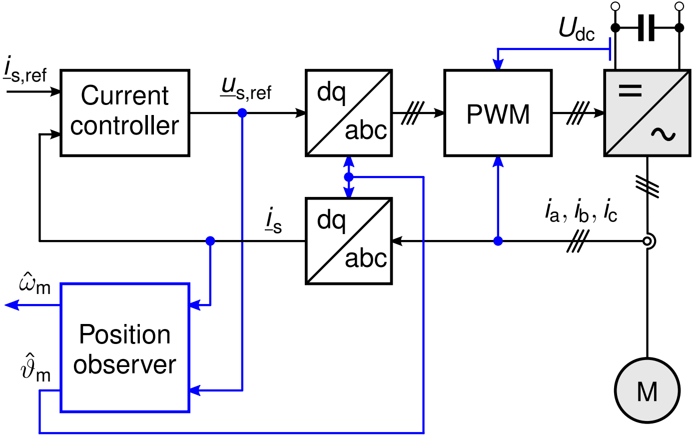
Fundamental-Excitation-Based Methods

Signal-Injection Method

Combined Method

Typical Sensorless Control System

- Fast current-control loop
- Position observer is often implemented in estimated rotor coordinates
- Dead-time effect and power-device voltage drops are compensated for in the PWM
- Torque and speed controllers are similar to those in sensored drives



The inverter nonlinearities can be approximately compensated for as $u'_{a,ref} = u_{a,ref} + \Delta u \,\mathrm{sign}(i_a)$, where $u'_{a,ref}$ is the compensated voltage reference and Δu is the compensation magnitude (typically a few volts). The compensation is used for the b- and c-phases as well.

Voltage Model in Stator Coordinates

- Stator flux estimator

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

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

- Flux estimate

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

- Flux angle estimate

$$\hat{\vartheta} = \arctan\left(\hat{\psi}_{\beta}/\hat{\psi}_{\alpha}\right)$$

- Rotor speed in steady state

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

- How to obtain the rotor angle $\hat{\vartheta}_{\mathrm{m}}$?

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

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

- Stator current components

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

- Current vector

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

- 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

- Adjustable model

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

- Stator current components

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

- Stator current vector

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

- Angle estimator

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

- Speed-adaptation law

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

  drives $\hat{i}_\mathrm{q} - i_\mathrm{q}$ to zero

- Also the d-component could be used in speed adaptation

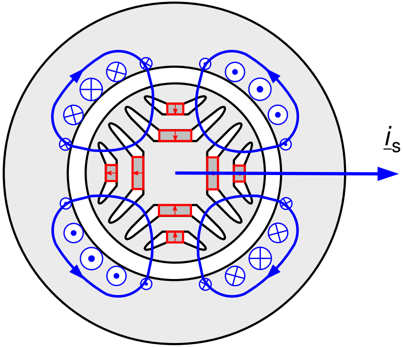
Outline

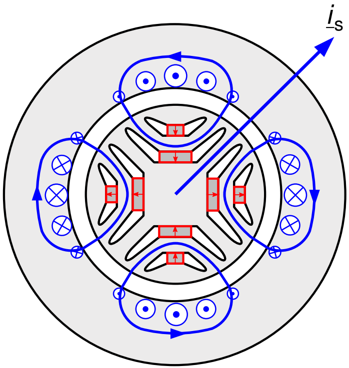
Fundamental-Excitation-Based Methods

Signal-Injection Method

Combined Method

Currents in the d and q Directions





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

$$\underline{\psi}_\mathrm{s} = L_\mathrm{d} i_\mathrm{d} + \psi_\mathrm{f}$$

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

$$\underline{\psi}_\mathrm{s} = \mathrm{j} L_\mathrm{q} i_\mathrm{q} + \psi_\mathrm{f}$$

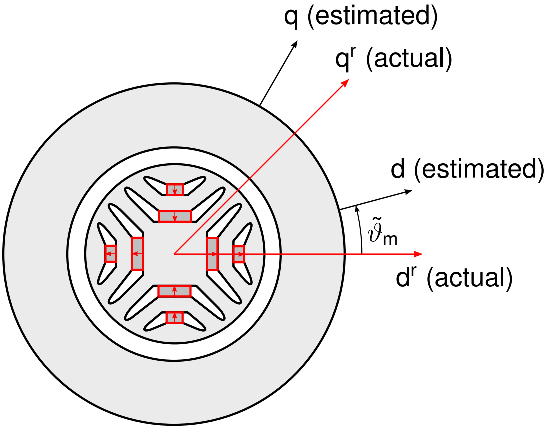
Position Estimation Error

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

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

- This leads to control errors

$$\underline{i}_\mathrm{s}^\mathrm{r} = \underline{i}_\mathrm{s}\, \mathrm{e}^{\mathrm{j}\tilde{\vartheta}_\mathrm{m}} \qquad \underline{\psi}_\mathrm{s}^\mathrm{r} = \underline{\psi}_\mathrm{s}\, \mathrm{e}^{\mathrm{j}\tilde{\vartheta}_\mathrm{m}}$$



Signal Injection: Alternating Excitation Signal

- Subscript i refers to injected high-frequency components
- Excitation voltage

$$u_{\mathrm{di}} = u_{\mathrm{i}} \cos(\omega_{\mathrm{i}} t)$$

  is injected in the d-axis

$$\underline{u}'_{\mathrm{s,ref}} = \underline{u}_{\mathrm{s,ref}} + u_{\mathrm{di}}$$

- Typical excitation frequencies $\omega_{\mathrm{i}}/(2\pi) = 500 \ldots 1\,000$ Hz

- Injected flux-linkage components in estimated rotor coordinates

$$\psi_{\mathrm{di}} = \frac{u_{\mathrm{i}}}{\omega_{\mathrm{i}}} \sin(\omega_{\mathrm{i}} t)$$
$$\psi_{\mathrm{qi}} = 0$$

  where $R_{\mathrm{s}} = 0$ and $\omega_{\mathrm{m}} = 0$ is assumed
- Injected flux components in actual rotor coordinates

$$\psi^{\mathrm{r}}_{\mathrm{di}} = \frac{u_{\mathrm{i}}}{\omega_{\mathrm{i}}} \sin(\omega_{\mathrm{i}} t) \cos \tilde{\vartheta}_{\mathrm{m}}$$
$$\psi^{\mathrm{r}}_{\mathrm{qi}} = \frac{u_{\mathrm{i}}}{\omega_{\mathrm{i}}} \sin(\omega_{\mathrm{i}} t) \sin \tilde{\vartheta}_{\mathrm{m}}$$

- Resulting current components in actual rotor coordinates

$$i_{\mathrm{di}}^{\mathrm{r}} = \psi_{\mathrm{di}}^{\mathrm{r}}/L_{\mathrm{d}}$$
$$i_{\mathrm{qi}}^{\mathrm{r}} = \psi_{\mathrm{qi}}^{\mathrm{r}}/L_{\mathrm{q}}$$

- Component in the estimated q-direction

$$\begin{aligned} i_{\mathrm{qi}} &= -i_{\mathrm{di}}^{\mathrm{r}} \sin\tilde{\vartheta}_{\mathrm{m}} + i_{\mathrm{qi}}^{\mathrm{r}} \cos\tilde{\vartheta}_{\mathrm{m}} \\ &= \frac{u_{\mathrm{i}}}{2\omega_{\mathrm{i}}} \frac{L_{\mathrm{d}} - L_{\mathrm{q}}}{L_{\mathrm{d}} L_{\mathrm{q}}} \sin(2\tilde{\vartheta}_{\mathrm{m}}) \sin(\omega_{\mathrm{i}} t) \end{aligned}$$

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

- Demodulation

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

- Low-pass filtering

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

- Error signal ϵ is roughly proportional to the position estimation error

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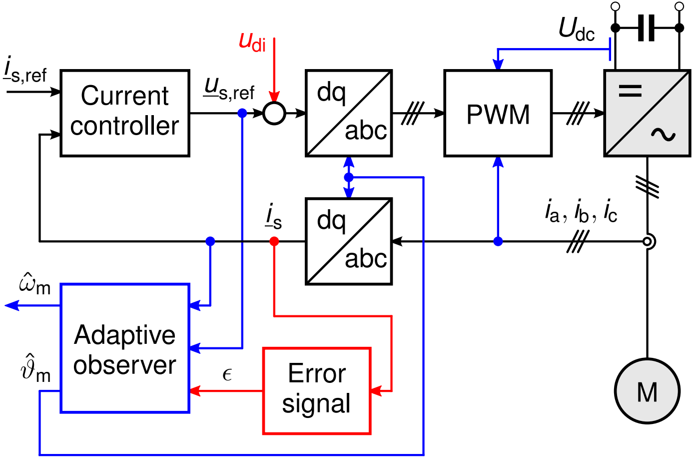
Sensorless Control System With Signal Injection

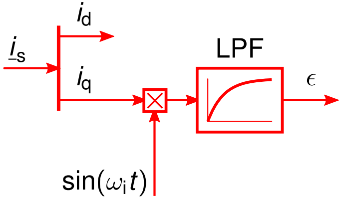
- Excitation voltage u_{di} is nonzero only at low speeds
- Speed-adaptive observer is augmented to exploit information from signal injection



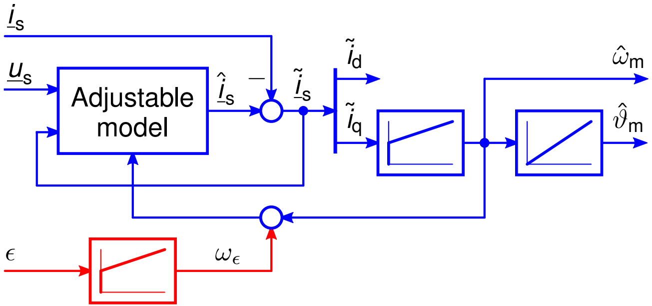
Speed-Adaptive Observer Augmented With Signal Injection

Error signal calculation

Delay and cross-saturation compensations are omitted in the figure for simplicity

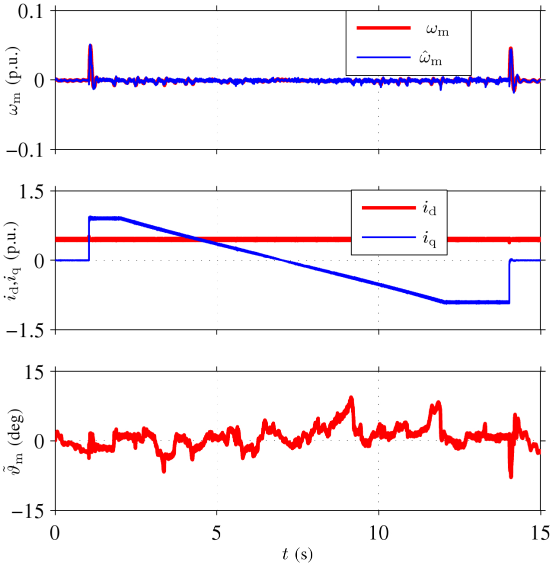


Adaptive observer (augmented with error signal)

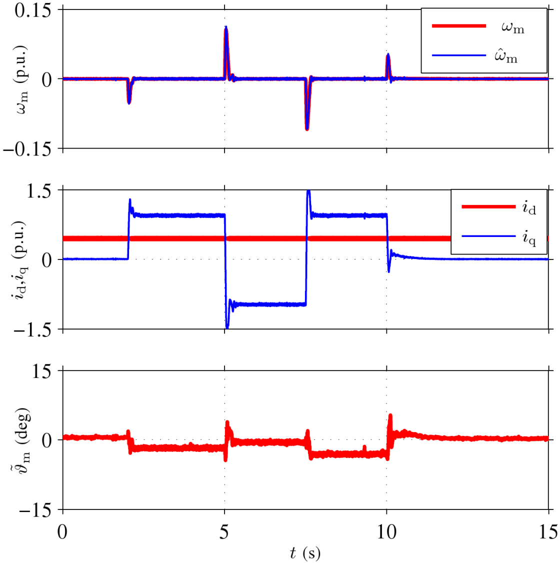


Experimental Results: 6.7-kW SyRM

- SyRM drive is operated in the torque-control mode
- Torque reference is reversed
- Speed reference of the load machine is kept at 0



- SyRM drive is operated in the speed-control mode
- Speed reference is kept at 0
- Load-torque steps: $0 \to T_\mathrm{N} \to -T_\mathrm{N} \to T_\mathrm{N} \to 0$



Sensorless Control: Problems and Properties

- Sources of errors in the position estimation
  - Parameter errors: $\hat{R}_s$ is important at low speeds
  - Accuracy of the stator voltage (inverter nonlinearities)
- Sustained operation at zero stator frequency is not possible (under the load torque) unless signal injection is applied
- Most demanding applications still need a speed or position sensor

Other Control Challenges

- High saliency ratio and low PM flux
- High stator frequency, which increases sensitivity to
  - Time delays
  - Discretization
- Parameter variations
  - Magnetic saturation
  - Effect of temperature variations on the stator resistance and PM flux
  - Skin effect (in form-wounded stator windings)
- Identification of the motor parameters
  - Self-commissioning during the drive start-up
  - Finite-element analysis?

Further Reading

- F. Blaabjerg et al., “Improved modulation techniques for PWM-VSI drives,” *IEEE Trans. Ind. Electron.*, vol. 44, 1997.
- M. Corley and R.D. Lorenz, “Rotor position and velocity estimation for a salient-pole permanent magnet synchronous machine at standstill and high speeds,” *IEEE Trans. Ind. Applicat.*, vol. 43, 1998.
- M. Hinkkanen et al. “A combined position and stator-resistance observer for salient PMSM drives: design and stability analysis,” *IEEE Trans. Pow. Electron.*, vol. 27, 2012.
- T. Tuovinen and M. Hinkkanen, “Adaptive full-order observer with high-frequency signal injection for synchronous reluctance motor drives,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, 2014.