



**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
  - ▶ 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)
  - ▶ Rely on magnetic anisotropy,  $L_d \neq L_q$  is necessary
  - ▶ 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

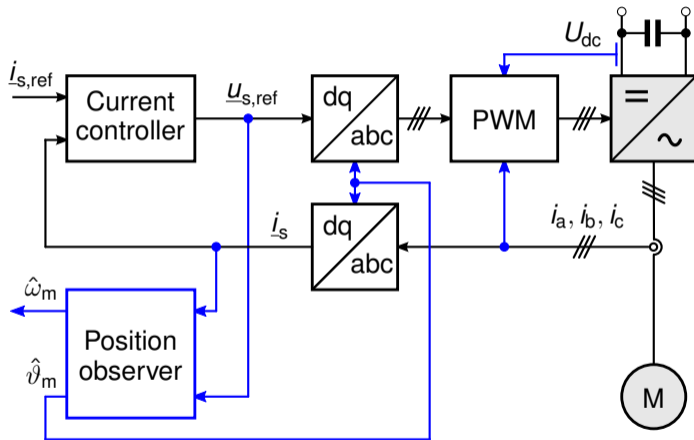
## Fundamental-Excitation-Based Methods

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 sensed drives



The inverter nonlinearities can be approximately compensated for as  $u'_{a,ref} = u_{a,ref} + \Delta u \text{sign}(i_a)$ , where  $u'_{a,ref}$  is the compensated voltage reference and  $\Delta u$  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

$$\frac{d\hat{\underline{\psi}}_s^s}{dt} = \underline{u}_s^s - \hat{R}_s \underline{i}_s^s \Rightarrow$$
$$\hat{\underline{\psi}}_s^s = \int (\underline{u}_s^s - \hat{R}_s \underline{i}_s^s) dt$$

- ▶ Flux estimate

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

- ▶ Flux angle estimate

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

- ▶ Rotor speed in steady state

$$\hat{\omega}_m = \frac{d\hat{\vartheta}}{dt}$$

- ▶ How to obtain the rotor angle  $\hat{\vartheta}_m$ ?

## 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  $\hat{R}_s$  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

$$\frac{d\hat{\underline{\psi}}_s}{dt} = \underline{u}_s - \hat{R}_s \hat{i}_s - j\hat{\omega}_m \hat{\underline{\psi}}_s$$

- ▶ Stator current components

$$\hat{i}_d = (\hat{\psi}_d - \hat{\psi}_f) / \hat{L}_d$$

$$\hat{i}_q = \hat{\psi}_q / \hat{L}_q$$

- ▶ Current vector

$$\hat{\underline{i}}_s = \hat{i}_d + j\hat{i}_q$$

- ▶ Rotor position estimator

$$\frac{d\hat{\vartheta}_m}{dt} = \hat{\omega}_m$$

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



# Speed-Adaptive Observer

- ▶ Adjustable model

$$\frac{d\hat{\psi}_s}{dt} = \underline{u}_s - \hat{R}_s \hat{i}_s - j\hat{\omega}_m \hat{\psi}_s + \underline{k}_1(i_d - \hat{i}_d) + \underline{k}_2(i_q - \hat{i}_q)$$

- ▶ Stator current components

$$\hat{i}_d = (\hat{\psi}_d - \hat{\psi}_f) / \hat{L}_d$$
$$\hat{i}_q = \hat{\psi}_q / \hat{L}_q$$

- ▶ Stator current vector

$$\hat{i}_s = \hat{i}_d + j\hat{i}_q$$

- ▶ Rotor position estimator

$$\frac{d\hat{\vartheta}_m}{dt} = \hat{\omega}_m$$

- ▶ Speed-adaptation law

$$\hat{\omega}_m = k_p(i_q - \hat{i}_q) + k_i \int (i_q - \hat{i}_q) dt$$

drives  $\hat{i}_q - i_q$  to zero

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

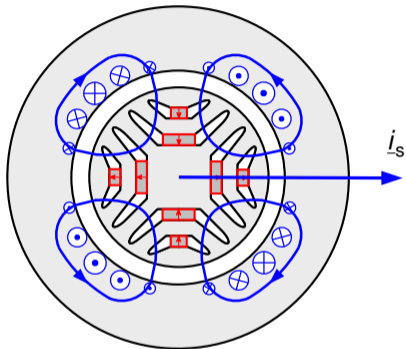
# Outline

Fundamental-Excitation-Based Methods

**Signal-Injection Method**

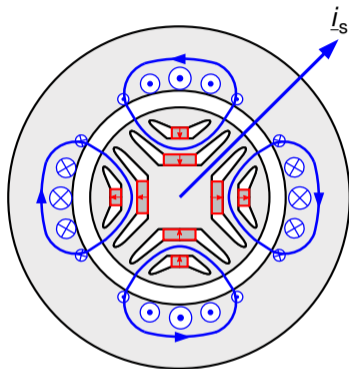
Combined Method

# Currents in the d and q Directions



$$\underline{i}_s = i_d + j0$$

$$\underline{\psi}_s = L_d i_d + \psi_f$$



$$\underline{i}_s = 0 + j i_q$$

$$\underline{\psi}_s = j L_q i_q + \psi_f$$

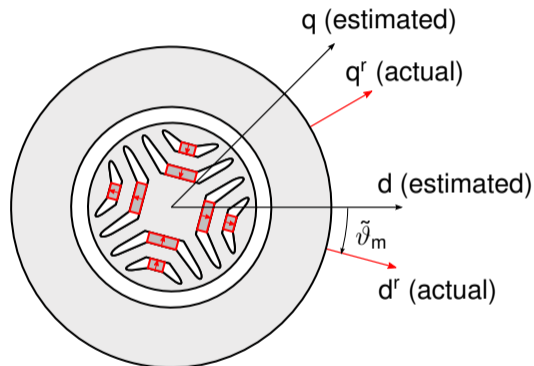
# Position Estimation Error

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

$$\tilde{\vartheta}_m = \vartheta_m - \hat{\vartheta}_m$$

- ▶ This leads to control errors

$$\underline{i}_s^r = \underline{i}_s e^{-j\tilde{\vartheta}_m} \quad \underline{\psi}_s^r = \underline{\psi}_s e^{-j\tilde{\vartheta}_m}$$



# Signal Injection: Alternating Excitation Signal

- ▶ Subscript  $i$  refers to injected high-frequency components
- ▶ **Excitation voltage**

$$u_{di} = u_i \cos(\omega_i t)$$

is injected in the d-axis

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

- ▶ Typical excitation frequencies  
 $\omega_i / (2\pi) = 500 \dots 1\,000 \text{ Hz}$

- ▶ Injected flux components in estimated rotor coordinates

$$\psi_{di} = \frac{u_i}{\omega_i} \sin(\omega_i t)$$

$$\psi_{qi} = 0$$

where  $R_s = 0$  and  $\omega_m = 0$  is assumed

- ▶ Injected flux components in actual rotor coordinates

$$\psi_{di}^r = \frac{u_i}{\omega_i} \sin(\omega_i t) \cos \tilde{\vartheta}_m$$

$$\psi_{qi}^r = -\frac{u_i}{\omega_i} \sin(\omega_i t) \sin \tilde{\vartheta}_m$$

- ▶ Resulting current components in actual rotor coordinates

$$i_{di}^r = \psi_{di}^r / L_d$$

$$i_{qi}^r = \psi_{qi}^r / L_q$$

- ▶ Component in the estimated q-direction

$$\begin{aligned} i_{qi} &= i_{di}^r \sin \tilde{\vartheta}_m + i_{qi}^r \cos \tilde{\vartheta}_m \\ &= \frac{u_i}{2\omega_i} \frac{L_q - L_d}{L_d L_q} \sin(2\tilde{\vartheta}_m) \sin(\omega_i t) \end{aligned}$$

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

- ▶ Demodulation

$$\begin{aligned} & i_{qi} \sin(\omega_i t) \\ &= \frac{u_i}{4\omega_i} \frac{L_q - L_d}{L_d L_q} \sin(2\tilde{\vartheta}_m) [1 - \sin(2\omega_i t)] \end{aligned}$$

- ▶ Low-pass filtering

$$\begin{aligned} \epsilon &= \text{LPF} \{ i_{qi} \sin(\omega_i t) \} \\ &= \frac{u_i}{4\omega_i} \frac{L_q - L_d}{L_d L_q} \sin(2\tilde{\vartheta}_m) \end{aligned}$$

- ▶ Error signal  $\epsilon$  is roughly proportional to the position estimation error

# Outline

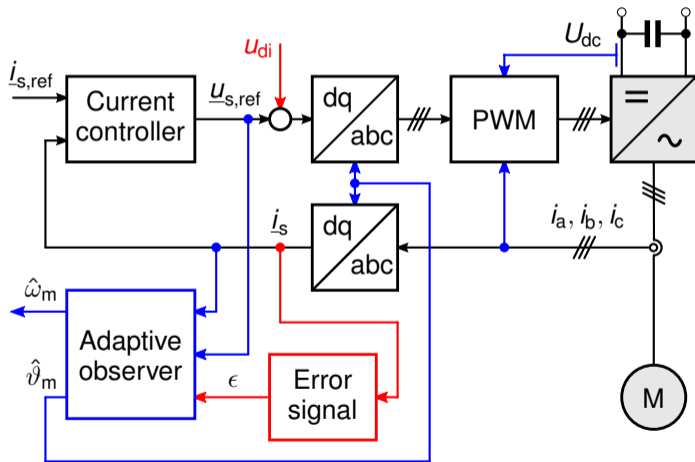
Fundamental-Excitation-Based Methods

Signal-Injection Method

**Combined Method**

# 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

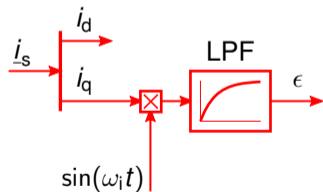




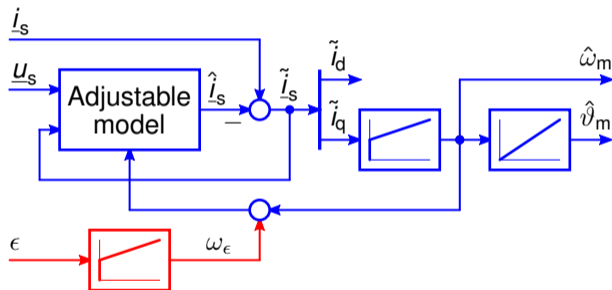
# Speed-Adaptive Observer Augmented With Signal Injection

## Error signal calculation

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

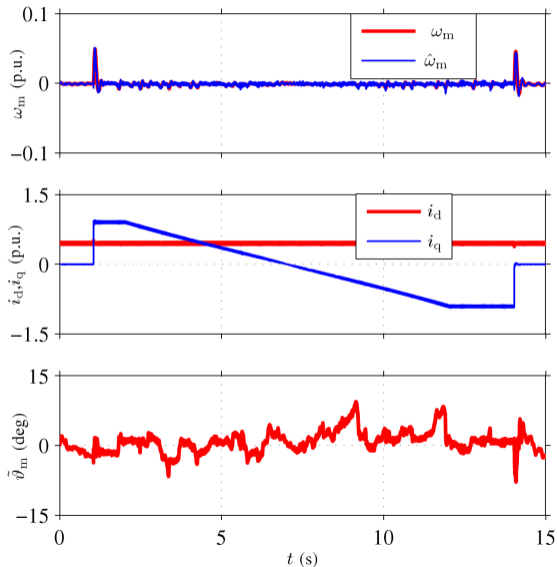


## Adaptive observer (augmented with error signal)

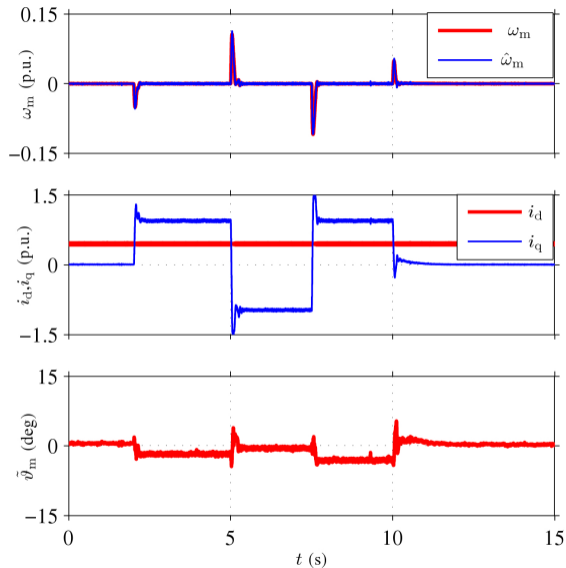


# Experimental Results: 6.7-kW SyRM

- ▶ 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:  
 $0 \rightarrow T_N \rightarrow -T_N \rightarrow T_N \rightarrow 0$



# 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-wound 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.