Lecture 10: Direct Torque 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 typical properties of sensorless control
- Explain the operating principle of direct torque control (DTC), including the switching logic in normal operation

The induction motor drive is considered in this lecture, but the methods can be modified for synchronous motors as well.

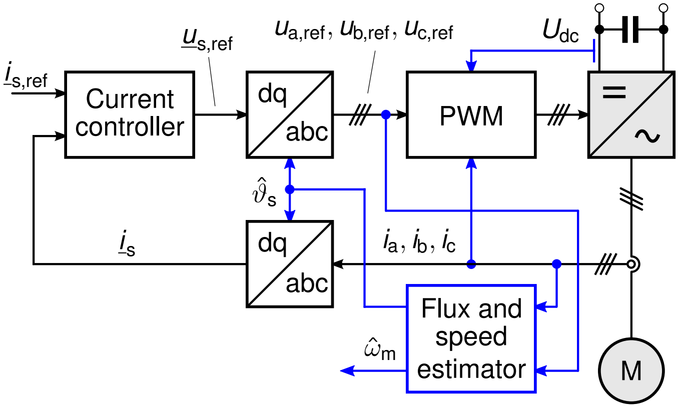
Outline

Sensorless Vector Control of an Induction Motor

Direct Torque Control

Example: Sensorless Control System for an Induction Motor

- 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
- Stability and performance depend on the flux estimator coordinates



The inverter nonlinearities can be approximately compensated for as $u'_{\mathrm{a,ref}} = u_{\mathrm{a,ref}} + \Delta u\, \mathrm{sign}(i_{\mathrm{a}})$, where $u'_{\mathrm{a,ref}}$ 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 Flux Estimator in Stator Coordinates

- Stator voltage equation is simulated in real time

$$\frac{\mathrm{d}\hat{\underline{\psi}}_\mathrm{s}^\mathrm{s}}{\mathrm{d}t} = \underline{u}_\mathrm{s}^\mathrm{s} - \hat{R}_\mathrm{s}\underline{i}_\mathrm{s}^\mathrm{s} \qquad \text{or} \qquad \hat{\underline{\psi}}_\mathrm{s}^\mathrm{s} = \int \left(\underline{u}_\mathrm{s}^\mathrm{s} - \hat{R}_\mathrm{s}\underline{i}_\mathrm{s}^\mathrm{s}\right) \mathrm{d}t$$

- Pure integration: $\hat{\underline{\psi}}_\mathrm{s}^\mathrm{s}$ does not appear on the right-hand side
- Rotor flux estimate

$$\hat{\underline{\psi}}_\mathrm{R}^\mathrm{s} = \hat{\underline{\psi}}_\mathrm{s}^\mathrm{s} - \hat{L}_\sigma \underline{i}_\mathrm{s}^\mathrm{s}$$

- Estimated rotor-flux angle

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

- Could be implemented in estimated rotor flux coordinates

Properties of the Voltage Model

- Speed sensor not needed
- Starting point for developing sensorless flux estimators
- Very sensitive to $\hat{R}_s$ at low speeds (depends also on $\hat{L}_\sigma$)
- Good accuracy at higher speeds (despite the parameter errors)
- Pure integration does not work in practice since the flux estimate will drift away from the origin (due to any offsets in measurements)
- Above problems can be partly solved by combining the voltage model with the flux-magnitude information from the current model $\Rightarrow$ observer

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For more details about observers, see, for example, M. Hinkkanen et al., "Reduced-order flux observers with stator-resistance adaptation for speed-sensorless induction motor drives," *IEEE Trans. Pow. Electron.*, 2010, and Z. Qu et al., "Gain scheduling of a full-order observer for sensorless induction motor drives," *IEEE Trans. Ind. Applicat.*, 2014.

Speed Estimation

- If the voltage-model based flux observer is used, the rotor speed can be estimated using the slip relation in estimated rotor flux coordinates

$$\hat{\omega}_\mathrm{m} = \hat{\omega}_\mathrm{s} - \hat{\omega}_\mathrm{r} = \hat{\omega}_\mathrm{s} - \frac{\hat{R}_\mathrm{R} i_\mathrm{q}}{\hat{\psi}_\mathrm{R}}$$

- Angular speed of the rotor flux vector

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

- Low-pass filtering of $\hat{\omega}_\mathrm{m}$ is typically needed

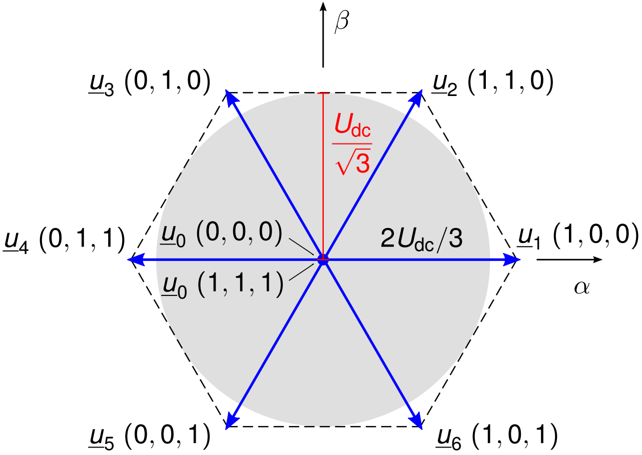
Sensorless Control: Problems and Properties

- Flux estimation at lowest speeds is difficult
- Error sources in the flux estimation
  - Parameter errors ($\hat{R}_\mathrm{s}$ is crucial at low speeds)
  - Errors in the stator voltage: inverter nonlinearities are typically compensated for but some error remains
- Sustained operation at zero stator frequency not possible (under the load torque)
- Most demanding applications still need a speed sensor

Outline

Direct Torque Control: Introduction

- Instantaneous values of the stator flux and torque are controlled directly by means of inverter switching states
  - Hysteresis control principle
  - Stator coordinates
  - No separate PWM
  - Typical sampling period 12.5 μs (80 kHz)
- Torque can be controlled at fastest possible rate of change without overshoot (ideally)



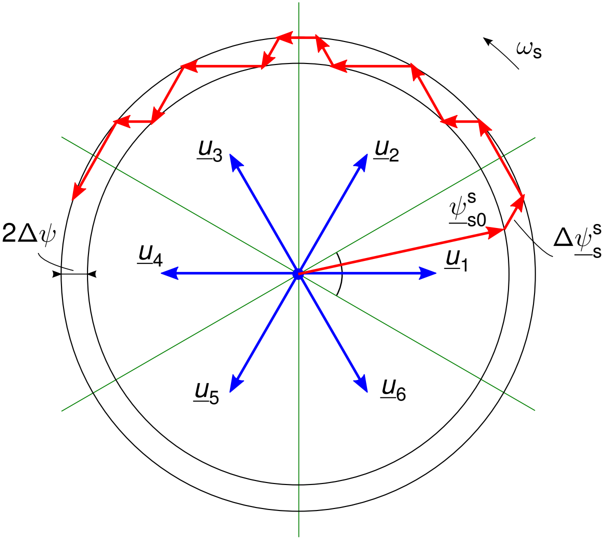
Control Principle

- Suitable voltage vector $\underline{u}_n$ is selected at each sampling period
- Change in the stator flux

$$\Delta\underline{\psi}_s^s = \int_0^{t_n} (\underline{u}_s^s - R_s \underline{i}_s^s)\mathrm{d}t \approx \underline{u}_n t_n$$

where t_n is multiple of the sampling period

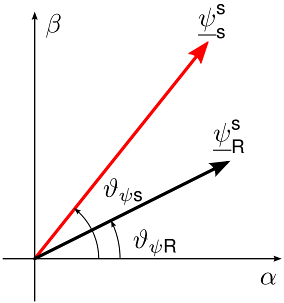
- Which voltage vectors are applied in the figure?

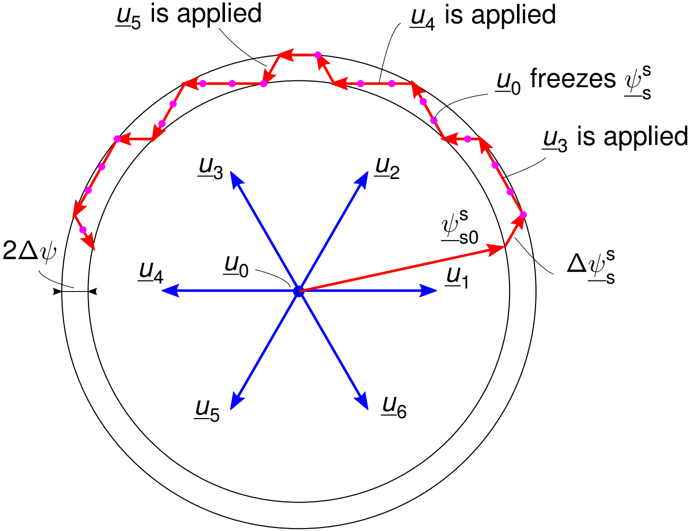


- Torque depends on $\vartheta_{\psi\mathrm{s}}$

$$T_\mathrm{M} = \frac{3p}{2}\frac{1}{L_\sigma}\,\mathrm{Im}\left\{\underline{\psi}_\mathrm{R}^*\underline{\psi}_\mathrm{s}\right\}$$
$$= \frac{3p}{2}\frac{1}{L_\sigma}\psi_\mathrm{R}\psi_\mathrm{s}\sin(\vartheta_{\psi\mathrm{s}} - \vartheta_{\psi\mathrm{R}})$$

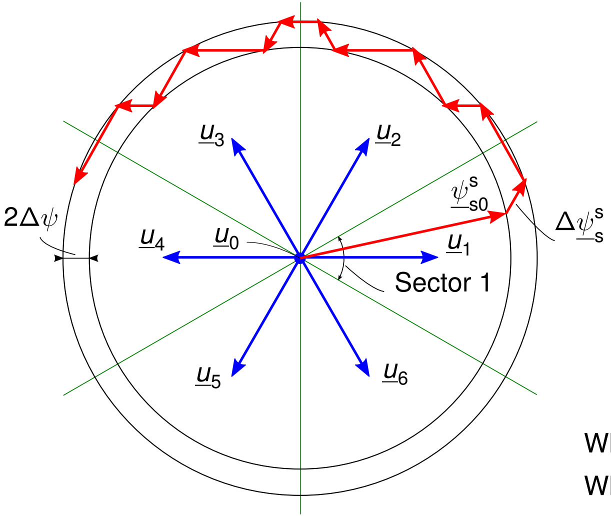
- Rotor flux vector $\underline{\psi}_\mathrm{R}^\mathrm{s}$ is almost constant during a very short sampling period
- Torque can be changed via $\vartheta_{\psi\mathrm{s}}$

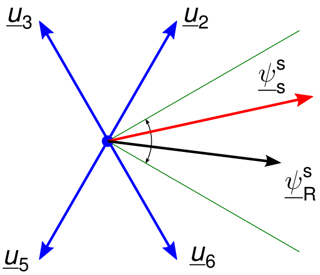




$\underline{u}_5$ is applied
$\underline{u}_4$ is applied
$\underline{u}_0$ freezes $\underline{\psi}_s^s$
$\underline{u}_3$ is applied
$\underline{u}_3$
$\underline{u}_2$
$\underline{\psi}_{s0}^s$
$2\Delta\psi$
$\underline{u}_4$
$\underline{u}_0$
$\underline{u}_1$
$\Delta\underline{\psi}_s^s$
$\underline{u}_5$
$\underline{u}_6$

Six Sectors: Selection of Vectors in Sector 1

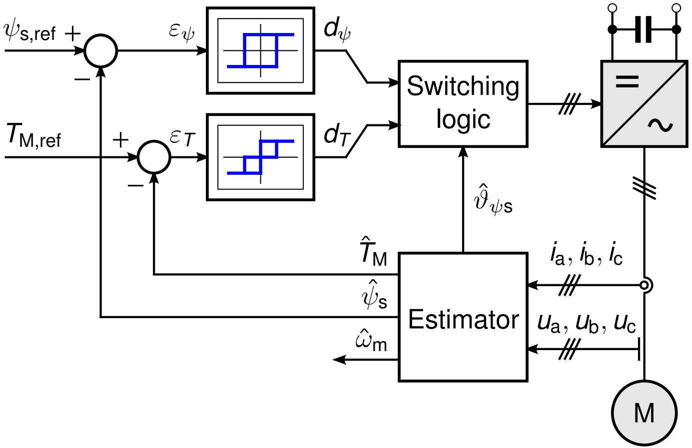


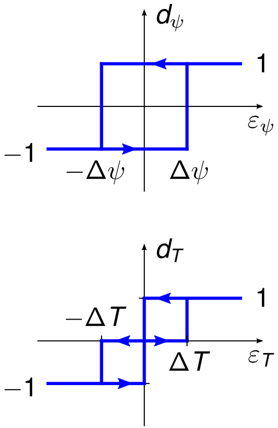


Which vectors would increase $|\underline{\psi}_s|$?

Which vectors would increase T_M?

Control System





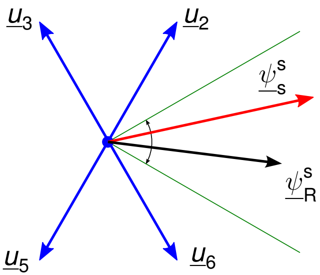
Principle of the Switching Logic

- Hysteresis flux controller

$$d_\psi(k) = \begin{cases} -1 & \text{if } \varepsilon_\psi(k) < -\Delta\psi \\ 1 & \text{if } \varepsilon_\psi(k) > \Delta\psi \\ d_\psi(k-1) & \text{otherwise} \end{cases}$$

- Hysteresis torque controller can be implemented similarly
- Switching logic in Sector 1

d_T	1	1	0	0	-1	-1
d_ψ	1	-1	1	-1	1	-1
Vector	$\underline{u}_2$	$\underline{u}_3$	0	0	$\underline{u}_6$	$\underline{u}_5$



Stator Flux and Torque Estimation

- Voltage-model estimator can be used

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

- Similar problems (and their remedies) as in sensorless vector control
- Torque estimate

$$\hat{T}_\mathrm{M} = \frac{3p}{2}\,\mathrm{Im}\left\{\underline{i}_\mathrm{s}^\mathrm{s}\underline{\hat{\psi}}_\mathrm{s}^{\mathrm{s}*}\right\}$$

Properties of DTC

- Fast dynamic response can be achieved
- Switching frequency varies with the operating point and motor parameters
- Hysteresis control requires a high sampling frequency and computing speed in order to detect when the flux or the torque gets outside the hysteresis band
- Flux estimation at low speeds without the speed sensor can be a difficult problem (the same problem also in sensorless vector control)
- Can be modified for synchronous motors