Aalto University
School of Electrical
Engineering

Lecture 10: Field-Oriented Control

ELEC-E8405 Electric Drives

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Learning Outcomes

After this lecture and exercises you will be able to:

- Explain the basic principles of field-oriented control of a permanent-magnet synchronous motor
- Draw and explain the block diagram of field-oriented control
- Calculate the operating points of the motor in rotor coordinates

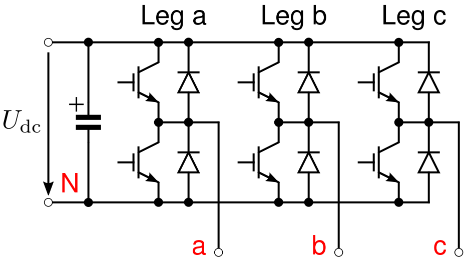
Outline

3-Phase Inverter

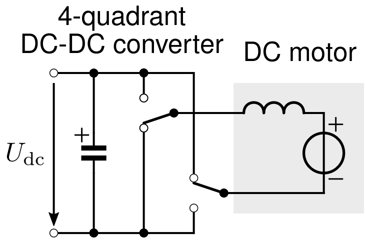
Field-Oriented Control

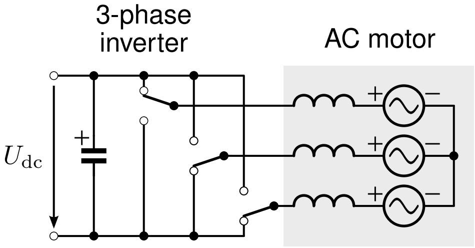
Current and Voltage Limits

3-Phase Inverter

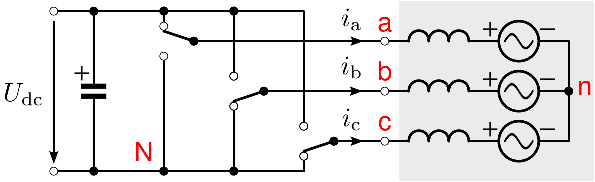


DC-DC Converter vs. 3-Phase Inverter





Space Vector of the Converter Output Voltages



- Zero-sequence voltage does not affect the phase currents
- Reference potential of the phase voltages can be freely chosen

$$\boldsymbol{u}_{\mathrm{s}}^{\mathrm{s}} = \frac{2}{3}\left(u_{\mathrm{an}} + u_{\mathrm{bn}}\mathrm{e}^{\mathrm{j}2\pi/3} + u_{\mathrm{cn}}\mathrm{e}^{\mathrm{j}4\pi/3}\right)$$ Neutral n as a reference

$$= \frac{2}{3}\left(u_{\mathrm{aN}} + u_{\mathrm{bN}}\mathrm{e}^{\mathrm{j}2\pi/3} + u_{\mathrm{cN}}\mathrm{e}^{\mathrm{j}4\pi/3}\right)$$ Negative DC bus N as a reference

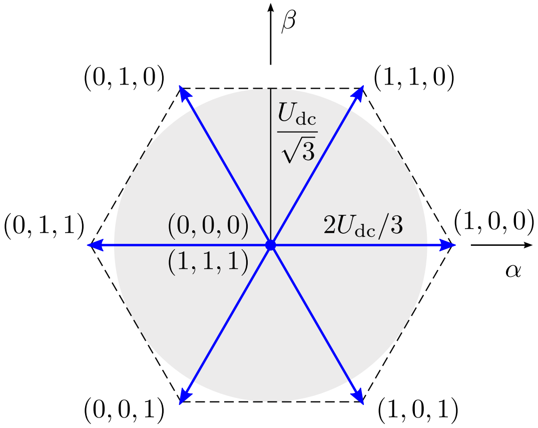
- Converter output voltage vector

$$\boldsymbol{u}_\mathrm{s}^\mathrm{s} = \frac{2}{3}\left(u_\mathrm{aN} + u_\mathrm{bN}\mathrm{e}^{\mathrm{j}2\pi/3} + u_\mathrm{cN}\mathrm{e}^{\mathrm{j}4\pi/3}\right)$$
$$= \frac{2}{3}\left(q_\mathrm{a} + q_\mathrm{b}\mathrm{e}^{\mathrm{j}2\pi/3} + q_\mathrm{c}\mathrm{e}^{\mathrm{j}4\pi/3}\right) U_\mathrm{dc}$$

  where q_abc are the switching states (either 0 or 1)

- Vector $(1, 0, 0)$ as an example

$$\boldsymbol{u}_\mathrm{s}^\mathrm{s} = \frac{2U_\mathrm{dc}}{3}$$



Switching-Cycle Averaged Voltage

- Using PWM, any voltage vector inside the voltage hexagon can be produced in average over the switching period

$$\overline{\boldsymbol{u}}_\mathrm{s}^\mathrm{s} = \frac{2}{3}\left(d_\mathrm{a} + d_\mathrm{b}\mathrm{e}^{\mathrm{j}2\pi/3} + d_\mathrm{c}\mathrm{e}^{\mathrm{j}4\pi/3}\right) U_\mathrm{dc}$$

  where d_abc are the duty ratios (between 0...1)
- Maximum magnitude of the voltage vector is $u_\mathrm{max} = U_\mathrm{dc}/\sqrt{3}$ in linear modulation (the circle inside the hexagon)
- PWM can be implemented using the carrier comparison
- Only switching-cycle averaged quantities will be needed in the following (overlining will be omitted for simplicity)

The 3-phase PWM and the space-vector current controller can be realized using similar techniques as we used in connection with the DC-DC converters and the DC motors, respectively. However, details of these methods are out of the scope of this course.

Outline

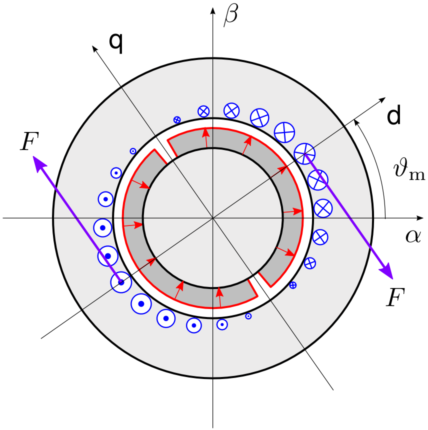
3-Phase Inverter

Field-Oriented Control

Current and Voltage Limits

Permanent-Magnet Synchronous Motor

- Current distribution produced by a 3-phase winding is illustrated in the figure
- Torque is constant only if the supply frequency equals the electrical rotor speed $\omega_\mathrm{m} = \mathrm{d}\vartheta_\mathrm{m}/\mathrm{d}t$
- For controlling the torque, the current distribution has to be properly placed in relation to the rotor
- Rotor position has to be measured (or estimated)



Field-Oriented Control

- Resembles cascaded control of DC motors
- Automatically synchronises the supply frequency with the rotating rotor field
- Torque can be controlled simply via i_q in rotor coordinates
- Field-oriented control of other AC motors is quite similar to that of a surface-mounted permanent-magnet synchronous motor considered in these lectures

Synchronous Motor Model in Rotor Coordinates

- Stator voltage

$$\boldsymbol{u}_\mathrm{s} = R_\mathrm{s}\boldsymbol{i}_\mathrm{s} + \frac{\mathrm{d}\boldsymbol{\psi}_\mathrm{s}}{\mathrm{d}t} + \mathrm{j}\omega_\mathrm{m}\boldsymbol{\psi}_\mathrm{s}$$

- Stator flux linkage

$$\boldsymbol{\psi}_\mathrm{s} = L_\mathrm{s}\boldsymbol{i}_\mathrm{s} + \psi_\mathrm{f}$$

- Torque is proportional to the q component of the current

$$\tau_\mathrm{M} = \frac{3n_\mathrm{p}}{2}\,\mathrm{Im}\left\{\boldsymbol{i}_\mathrm{s}\boldsymbol{\psi}_\mathrm{s}^*\right\} = \frac{3n_\mathrm{p}}{2}\psi_\mathrm{f} i_\mathrm{q}$$

Space-Vector and Coordinate Transformations

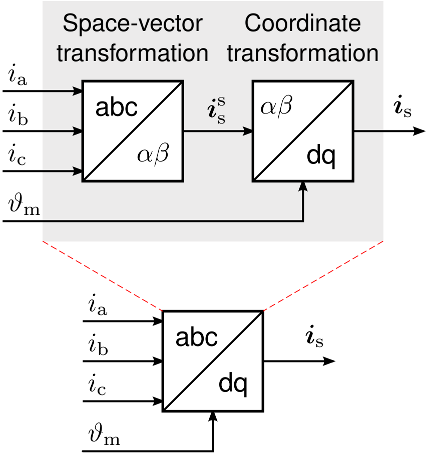
- Space-vector transformation (abc/$\alpha\beta$)

$$\boldsymbol{i}_\mathrm{s}^\mathrm{s} = \frac{2}{3}\left(i_\mathrm{a} + i_\mathrm{b}\mathrm{e}^{\mathrm{j}2\pi/3} + i_\mathrm{c}\mathrm{e}^{\mathrm{j}4\pi/3}\right)$$

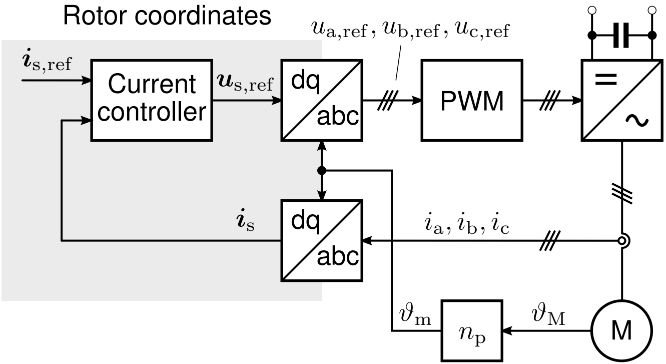
- Transformation to rotor coordinates ($\alpha\beta$/dq)

$$\boldsymbol{i}_\mathrm{s} = \boldsymbol{i}_\mathrm{s}^\mathrm{s}\mathrm{e}^{-\mathrm{j}\vartheta_\mathrm{m}}$$

- Combination of these two transformations is often referred to as abc/dq transformation
- Similarly, the inverse transformation is referred to as dq/abc transformation



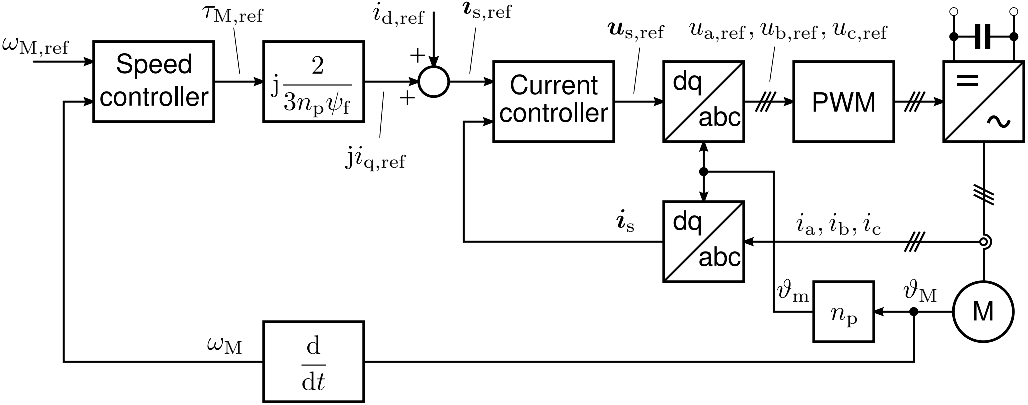
Fast Current Controller in Rotor Coordinates



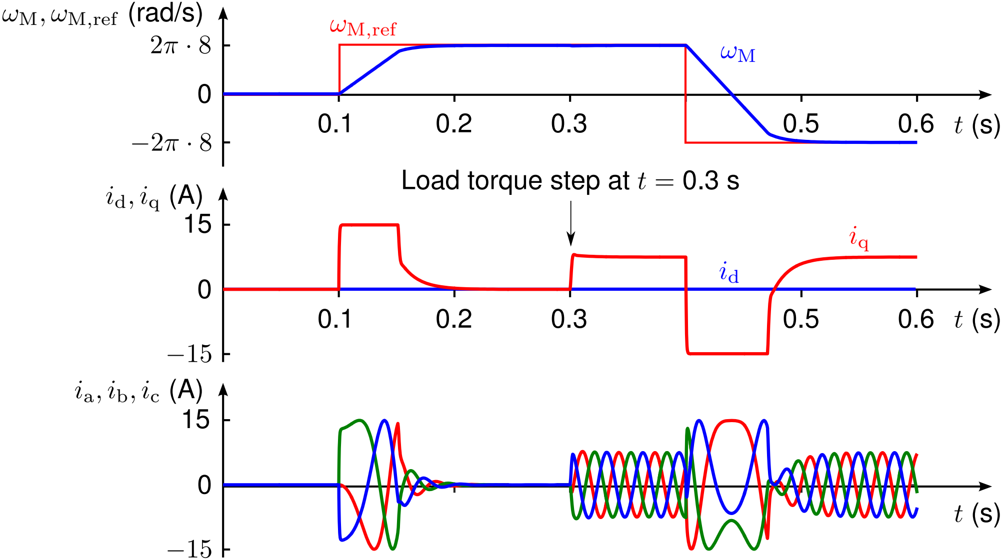
- Absolute rotor position ϑ_M has to be measured (or estimated)
- Current reference $\boldsymbol{i}_{s,ref} = i_{d,ref} + j i_{q,ref}$ is calculated in rotor coordinates

The current controller could consist, for example, of two similar real-valued PI-type controllers (one for i_d and another for i_q).

Field-Oriented Controller



- Control principle $i_{\mathrm{d,ref}} = 0$ minimises the resistive losses
- Speed controller is not needed in some applications



$\omega_\mathrm{M}, \omega_\mathrm{M,ref}$ (rad/s)
$\omega_\mathrm{M,ref}$
$2\pi \cdot 8$
ω_M
0
0.1
0.2
0.3
0.5
0.6
t (s)
$-2\pi \cdot 8$
Load torque step at $t = 0.3$ s
$i_\mathrm{d}, i_\mathrm{q}$ (A)
15
i_q
i_d
0
0.1
0.2
0.3
0.5
0.6
t (s)
-15
$i_\mathrm{a}, i_\mathrm{b}, i_\mathrm{c}$ (A)
15
0
t (s)
-15

Outline

3-Phase Inverter

Field-Oriented Control

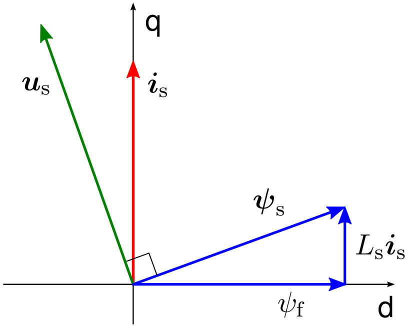
Current and Voltage Limits

Stator Voltage

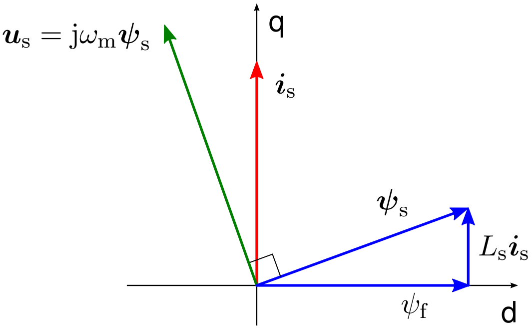
- In steady state, $\mathrm{d}/\mathrm{d}t = 0$ holds in rotor coordinates
- Steady-state stator voltage

$$\begin{aligned} \boldsymbol{u}_\mathrm{s} &= \mathrm{j}\omega_\mathrm{m}\boldsymbol{\psi}_\mathrm{s} \\ &= \mathrm{j}\omega_\mathrm{m}(L_\mathrm{s}\boldsymbol{i}_\mathrm{s} + \psi_\mathrm{f}) \\ &= \mathrm{j}\omega_\mathrm{m}(L_\mathrm{s}i_\mathrm{d} + \psi_\mathrm{f} + \mathrm{j}L_\mathrm{s}i_\mathrm{q}) \end{aligned}$$

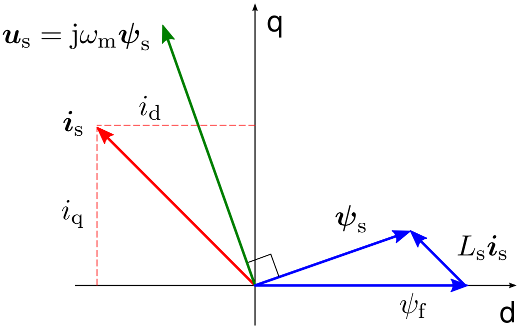
  when $R_\mathrm{s} = 0$ is assumed
- Voltage increases with the speed
- Maximum voltage magnitude u_max is limited by the DC-bus voltage U_dc



Field Weakening Above the Base Speed



Below the base speed: $i_\mathrm{d} = 0$



Above the base speed: $i_\mathrm{d} < 0$
in order to reduce $|\boldsymbol{\psi}_\mathrm{s}|$

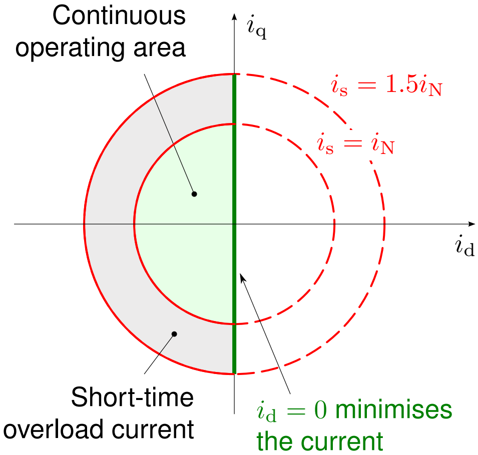
If a synchronous machine had a field winding instead of the permanent magnets, ψ_f could also be varied.

Current Limit

- Current limit

$$i_{\mathrm{s}}^2 = i_{\mathrm{d}}^2 + i_{\mathrm{q}}^2 \leq i_{\mathrm{max}}^2$$

- Example figure
  - Rated motor current i_{N}
  - Maximum converter current is assumed to be $1.5 i_{\mathrm{N}}$
- Motor tolerates short-time overload currents due to its longer thermal time constant



Voltage Limit

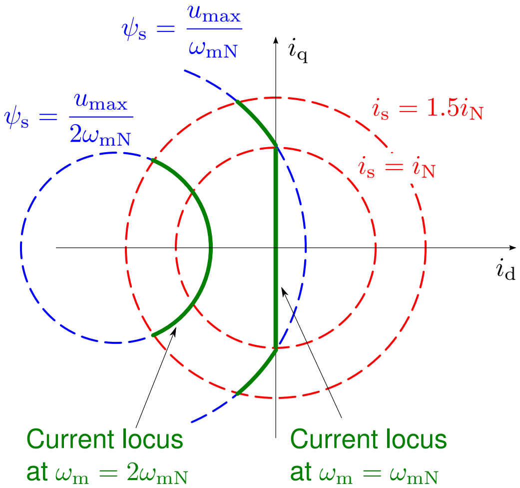
- Voltage limit

$$u_s^2 = \omega_m^2 \psi_s^2 \leq u_{max}^2$$

can be represented as a speed-dependent stator-flux limit

$$\psi_s^2 = (L_s i_d + \psi_f)^2 + (L_s i_q)^2 \leq \frac{u_{max}^2}{\omega_m^2}$$

- Example figure: current loci at two different speeds as the torque varies



Summary of Control Principles

- Control principle below the base speed

$$i_{\mathrm{d,ref}} = 0 \quad \text{and} \quad i_{\mathrm{q,ref}} = \frac{2\tau_{\mathrm{M,ref}}}{3n_{\mathrm{p}}\psi_{\mathrm{f}}}$$

- Field weakening ($i_{\mathrm{d}} < 0$) can be used to reach higher speeds
  - Nonzero i_{d} causes losses $(3/2)R_{\mathrm{s}}i_{\mathrm{d}}^2$
  - Risk of overvoltages if the current control is lost
  - Risk of demagnetizing the permanent magnets in some machines
- Current and voltage limits have to be taken into account