Control of Electric Drives

- Position Controllers
- Speed Controllers
- Current Controllers

Eastbavarian Technical University of Applied Sciences
- 11,000 students
- 8 faculties

Faculty of Electrical Engineering and Information Technology
- 1,500 students
- 3 Bachelor and 3 Master Courses

Prof. Anton Haumer
- Courses in Electrical Drives
- Courses in Basics of Electrical Engineering
- Courses in Modeling and Simulation with Modelica
Agenda

• Introduction
• Machine models
• Cascaded control
  • Current controller
  • Speed controller
  • Position controller
• Outlook:
  • Field weakening
  • Field Oriented Control
• References

MSL Machine models

• Modelica.Electrical.Machines
  • DC Machines QS and Transient
  • 3 phase transformers QS and Transient
  • Transient 3 phase machines, based on space phasor theory
    • Induction machines
    • Synchronous machines

QS=QuasiStatic = without electric but with mechanical transients
MSL Machine models

- Modelica.Magnetic.FundamentalWave and QuasiStatic.FundamentalWave
  - Multiphase phase machines
    - Induction machines
    - Synchronous machines
- Based on rotating magnetic field
- Same parameters, connectors, loss models compared with Modelica.Electrical.Machines
- Number of phases $m \geq 3$, $m \neq 2^n$
- Ready to be combined with power electronics (inverter) and control

Control of Electric Drives

- Easy to understand: permanent magnet DC machine
  FOC for rotatory field machines uses the same principles!
- Common approach: cascaded control
  - The loops can be set into operation one after another
- We have to take into account limitations:
  - DC voltage is limited (e.g. by the battery)
  - Current is limited (by the power electronic devices)
  - Speed is limited (mechanically, by the machine)
Permanent Magnet DC Machine

\[ T_A = \frac{L_A}{R_A} \to \frac{V_A - V_i}{R_A} = I_A + T_A \cdot \frac{dI_A}{dt} \]

Drive

Drive = Machine + Inverter (voltage source with dead-time)
- Dead time approximated by first order
- Measurements
- Communication: drive bus
- Parameterization: data record
Load

- Inertia
- Linear speed dependent torque
- Switched on at startTime

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Test the Drive (without Control)

Hands-On: Example VoltageSupplied

\[\text{stopTime} = 1.0, \quad \text{IntervalLength} = 0.001\]

referenceVoltage.height = data.VNom
Current Controller

- Take care of current filter (current ripple)

\[ I_{\text{Act},s} = G_p G_s = \frac{1}{(1 + s T_d)} \cdot \frac{1}{(1 + s T_A)} \cdot \frac{1}{(1 + s T_{st})} = R_A \cdot \frac{1}{(1 + s T_\sigma)(1 + s T_A)} \]

Controlled system: second order (small time constant \( T_\sigma = T_d + T_{st} \))

PI-controller

\[ G_C = \frac{V_{\text{Ref}}}{I_{\text{Err}}} = k_p \frac{1 + s T_{il}}{s T_{il}} \]

- Feed-forward of \( V_i = k \cdot \Phi \cdot \omega \)
- Limit the output voltage \( \rightarrow \) anti wind-up
Limited PI-Controller

- Limiting the output doesn't prevent the integrator from working
- → called „wind-up“ → We need an anti wind-up action.
- Feed–forward

Parameterization of the Current Controller

\[ G_o = G_C G_D G_S = \frac{k_{pl}}{R_A} \cdot \frac{1 + sT_{li}}{sT_{li}(1 + sT_\sigma)(1 + sT_A)} \]

Compensate the larger time constant →

\[ T_{li} = T_A = \frac{L_A}{R_A} \]

- Goal: smooth command action → absolute optimum

\[ \frac{|I_{\text{Act}}|}{|I_{\text{Ref.S}}|} = \frac{G_C G_D G_S}{1 + G_C G_D G_S} = 1 \]
Proportional Gain of the Current Controller

\[
G(s) = \frac{G_0}{1 + G_0} = \frac{1}{1 + \frac{R_A}{k_{pl}} s T_A (1 + s T_\sigma)} \xrightarrow{s=j\omega} \frac{1}{1 - \omega^2 \frac{R_A}{k_{pl}} T_A T_\sigma + j \omega \frac{R_A}{k_{pl}} T_A}
\]

\[
\left| \frac{G_0}{1 + G_0} \right|^2 = \frac{1}{1 + \omega^2 \left( \frac{R_A}{k_{pl}} T_A \right)^2 - 2 \frac{R_A}{k_{pl}} T_A T_\sigma + \omega^4 \left( \frac{R_A}{k_{pl}} T_A T_\sigma \right)^2}
\]

\[
\left( \frac{R_A}{k_{pl}} T_A \right)^2 - 2 \frac{R_A}{k_{pl}} T_A T_\sigma = 0 \rightarrow k_{pl} = \frac{T_A}{2 T_\sigma} = \frac{L_A}{2 T_\sigma}
\]

Resulting Command Action of the Current Controlled Drive

\[
\frac{I_{Act}}{I_{Ref}} = \frac{I_{Act,s}}{I_{Ref}} \cdot \frac{1}{1 + s T_{sl}} = \frac{1 + s T_{sl}}{1 + s^2 T_\sigma + s^2 2 T_\sigma^2}
\]

Compensate the numerator's zero with a first–order pre–filter.

\[
\frac{\tau_{Act}}{\tau_{Ref}} = \frac{I_{Act}}{I_{Ref}} = \frac{1}{1 + s^2 T_\sigma + s^2 2 T_\sigma^2} \approx \frac{1}{1 + s T_{sub}}
\]

\[
T_{sub} = 2 T_\sigma
\]
Current Controller

- Parameters calculated in the data record

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Test the Current Controlled Drive

Hands-On: Example CurrentControlled

stopTime=1.0, IntervalLength=0.001
referenceTorque.height=data.tauNom
currentController.data=data
Speed Control

System under control = current controlled drive + speed integrator

\[ G_D = \frac{\omega_{\text{act}}}{\tau_{\text{ref}}} = \frac{\tau_{\text{act}}}{\tau_{\text{ref}}} \cdot \frac{1}{sJ_{\text{tot}}} = \frac{1}{1 + sT_{\text{sub}}} \cdot \frac{1}{sJ_{\text{tot}}} = \frac{\omega_N}{\tau_N} \cdot \frac{1}{sT_m(1 + sT_{\text{sub}})} \]

Mechanical time constant

\[ T_m = (J_m + J_L) \frac{\omega_N}{\tau_N} \]

Speed Controller

- PI–controller
- Limiting the output (torque limit) \( \rightarrow \) anti wind–up
- Feed–forward not possible (load torque a–priori unknown)

\[ G_C = k_{p\omega} \frac{1 + sT_{\text{lo}}}{sT_{\text{lo}}} \]

\[ G_o = G_C G_D = k_{p\omega} \frac{1 + sT_{\text{lo}}}{sT_{\text{lo}}} \cdot \frac{\omega_N}{\tau_N} \cdot \frac{1}{sT_m(1 + sT_{\text{sub}})} \]
Parameterization of the Speed Controller

Goal: compensation of disturbance \( \Rightarrow \) symmetrical optimum

- Stability according to Nyquist:
  \[
  \arg(G_0) = -\pi + \arctan(\omega_D T_{l\omega}) - \arctan(\omega_D T_{sub}) > -\pi
  \]
- Phase response symmetrical w.r.t. gain crossover frequency
  \[
  |G_0(j\omega_D)| = 1
  \]
- Standard choice of parameter \( a = 2 \) from: ref. transfer function \( = 1 \)
- Phase margin
  \[
  \arg(G_0) \rightarrow \max: \frac{d[\arg(G_0)]}{d\omega} = \frac{T_{l\omega}}{1+(\omega_D T_{l\omega})^2} - \frac{T_{ers}}{1+(\omega_D T_{sub})^2} = 0 \rightarrow \omega_D = \frac{1}{\sqrt{T_{l\omega} T_{sub}}}
  \]

\[
T_{l\omega} = a^2 \cdot T_{sub} \rightarrow \omega_D = \frac{1}{a \cdot T_{sub}} = \frac{a}{T_{l\omega}} \rightarrow T_{l\omega} = a^2 \cdot T_{sub}
\]

\[
|G_0(j\omega_D)| = k_{p\omega} \cdot \frac{\omega_N \cdot a T_{sub}}{M_N \cdot T_m} = 1 \rightarrow k_{p\omega} = \frac{M_N \cdot T_m}{\omega_N \cdot a T_{sub}} = \frac{J_{tot}}{a T_{sub}}
\]

\[
\omega_{Act} = \frac{G_C G_D}{\omega_{ref}} = \frac{1 + s a^2 T_{sub}}{1 + G_C G_D} = \frac{1 + s a^2 T_{sub}}{1 + s a^2 T_{sub} + s^2 a^3 T_{sub}^2 + s^3 a^3 T_{sub}^3}
\]

Compensate the numerator's zero with a first-order pre-filter.
Speed Controller

\[
\begin{align*}
\omega_{\text{Act}} &= G_F \cdot \frac{G_C G_D}{1 + G_C G_D} = \frac{1}{1 + s^4 T_{\text{sub}} + s^2 8 T_{\text{sub}}^2 + s^3 8 T_{\text{sub}}^3} \approx \frac{1}{1 + s^4 T_{\text{sub}}}
\end{align*}
\]

\( \rightarrow \) Filter reference speed with by „ramping“ (SlewRateLimiter), 
\( \text{i.e. limit necessary torque for acceleration / deceleration} \)

Test the Speed Controlled Drive

Hands-On: Example SpeedControlled

```modelica
stopTime = 1.0, IntervalLength = 0.001
referenceSpeed.height = data.wNom
slewRateLimiter.Rising = data.aMax,
    initType = initialOutput, y_start = referenceSpeed.offset
currentController.data = data
speedController.data = data
load.startTime = 0.5
```
Position Control

System under control = speed controlled drive + position integrator

\[ G_D = \frac{\varphi_{Act}}{\omega_{Ref}} = \frac{1}{1 + s4T_{sub}} \cdot \frac{1}{s} \]

Position Controller

System under control has integral characteristic

\[ \Rightarrow \text{P-controller is sufficient} \]

\[ \frac{\varphi_{Act}}{\varphi_{Ref}} = \frac{G_C G_D}{1 + G_C G_D} = \frac{1}{1 + s k_p} + s^2 \frac{4T_{sub}}{k_p} = \frac{1}{1 + 2\theta Ts + (sT)^2} \]

Avoid overshot over reference end position \[ \Rightarrow \]

\[ \vartheta = \frac{1}{\sqrt{16k_p T_{sub}}} \geq 1 \rightarrow k_p \leq \frac{1}{16T_{sub}} \]
Position Controller

Reference position limits:
use PTP source

- Speed limit \( \frac{d\varphi}{dt} \)
- Torque limit \( \frac{d^2\varphi}{dt^2} \)

Test the Position Controlled Drive

Hands-On: Example PositionControlled

```modelica
stopTime=2.5, IntervalLength=0.001
referencePosition.height=50
der2Limiter.vMax=data.wMax, aMax=data.aMax,
initType=initialOutput,
y_start=referencePosition.offset, dery_start=0

currentController.data=data
speedController.data=data
positionController.data=data
load.speedDependent=false, startTime=2
```
Field Weakening

When $V_A = k \cdot \Phi \cdot \omega + R_A \cdot I_A$ reaches voltage limit:
flux has to be reduced \( \rightarrow \) field weakening

- Electrically excited DC machine: Excitation current controller
  similar to armature current controller:

$$\frac{V_E}{R_E} = I_E + \frac{L_E}{R_E} \cdot \frac{dI_E}{dt}$$

- Some adaptions in controllers due to $\Phi \sim \frac{1}{n}$.

<table>
<thead>
<tr>
<th>Base speed region</th>
<th>Field weakening</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi = \text{const.}$</td>
<td>$\phi \sim \frac{1}{\omega}$</td>
</tr>
<tr>
<td>$V \sim \omega$</td>
<td>$V = \text{const.}$</td>
</tr>
<tr>
<td>$I = \text{const.}$</td>
<td>$I = \text{const.}$</td>
</tr>
<tr>
<td>$\tau = \text{const.}$</td>
<td>$\tau \sim \frac{1}{\omega}$</td>
</tr>
<tr>
<td>$P \sim \omega$</td>
<td>$P = \text{const.}$</td>
</tr>
</tbody>
</table>

Power electronics defines current limit $\tau_{max} = k \cdot \Phi \cdot I_{max}$

Maximum torque of the machine $\tau_{Break\Down} \sim \Phi^2$
Field Oriented Control (FOC)

- Based on space phasors:
  \[ i = \frac{2}{3} \left( i_a + a \cdot i_b + a^2 \cdot i_c \right) \]
  → Animation of rotating field

- Orientation with respect to magnetic field →
  - Field current \( i_d \) like \( I_E \) excitation current
  - Torque current \( i_q \) like \( I_A \) armature current
  - Same control principle as DC machine!
EDrives Library

FOC of rotatory field machines with arbitrary number of phases $m \geq 3$

- Ready to use
  - induction machine with squirrel cage
  - permanent magnet synchronous machine
  - synchronous reluctance machine
- Controller parameter calculation in data records
  - Quasistatic machines and inverters
  - Transient machines and averaging inverters
  - Transient machines and switching inverters

⇒ www.edrives.eu

Contact: http://www.ltx.de/english.html
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Thank you for your attention!

Any questions?

anton.haumer@oth-regensburg.de
anton.haumer@edrives.eu

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