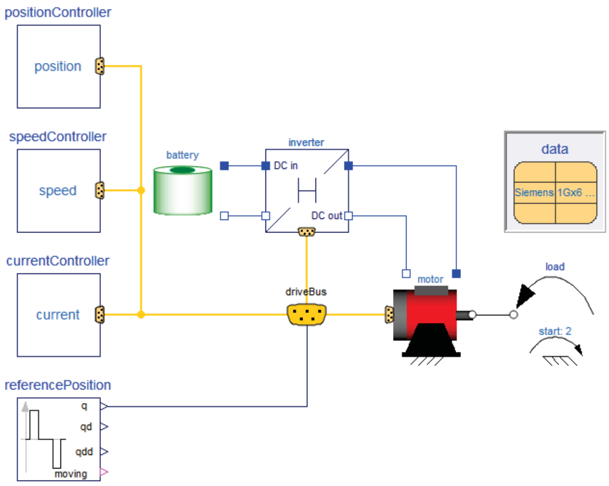
Control of Electric Drives



Eastbavarian Technical University of Applied Sciences www.oth-regensburg.de

- 11,000 students
- 8 faculties

Faculty of Electrical Engineering and Information Technology

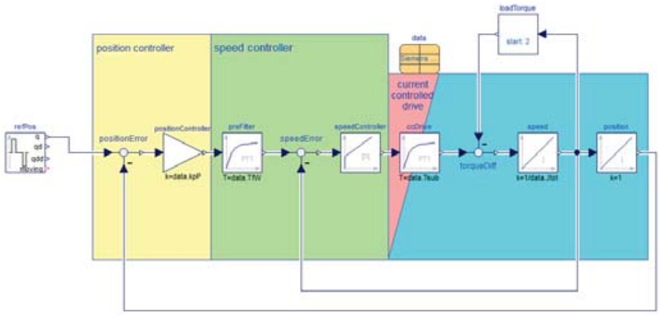
- 1,500 students
- 3 Bachelor and 3 Master Courses

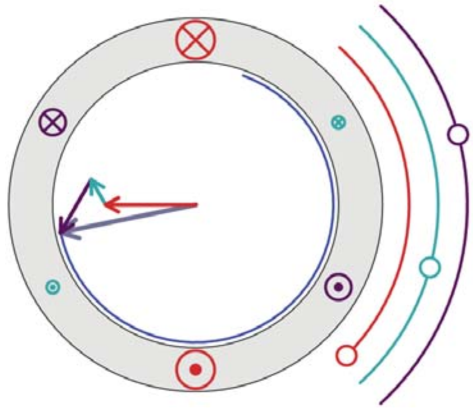
Prof. Anton Haumer

- Courses in Electrical Drives
- Courses in Basics of Electrical Engineering
- Courses in Modeling and Simulation with Modelica

Agenda

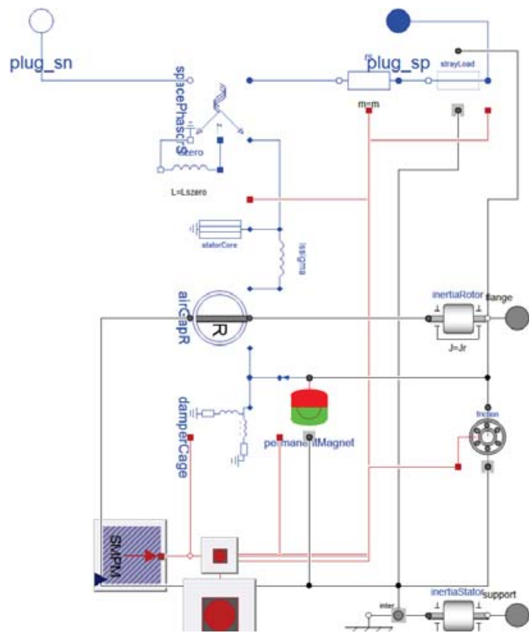
- Introduction
- Machine models
- Cascaded control
  - Current controller
  - Speed controller
  - Position controller
- Outlook:
  - Field weakening
  - Field Oriented Control
- References





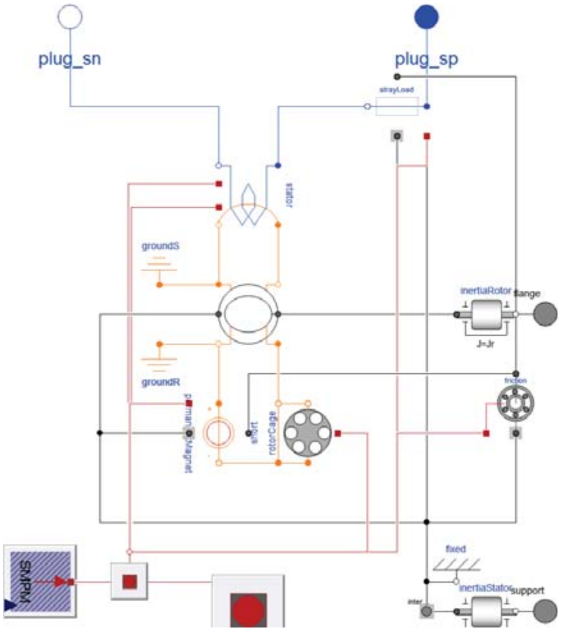
MSL Machine models

- 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

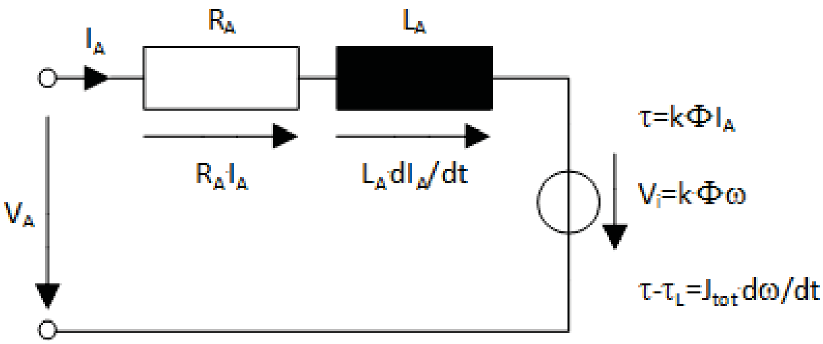


- Modelica.Magnetic.FundamentalWave and QuasiStatic.FundamentalWave
  - multiphase phase machines
    - Induction machines
    - Synchronous machines
- Based on rotating magnetic field
- Same parameters, connectors, loss models compared with Modelica.Electrical.Machines
- Number of phases $m \geq 3$, $m \neq 2^n$
- 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



$$T_A = \frac{L_A}{R_A} \rightarrow \frac{V_A - V_i}{R_A} = I_A + T_A \cdot \frac{dI_A}{dt}$$

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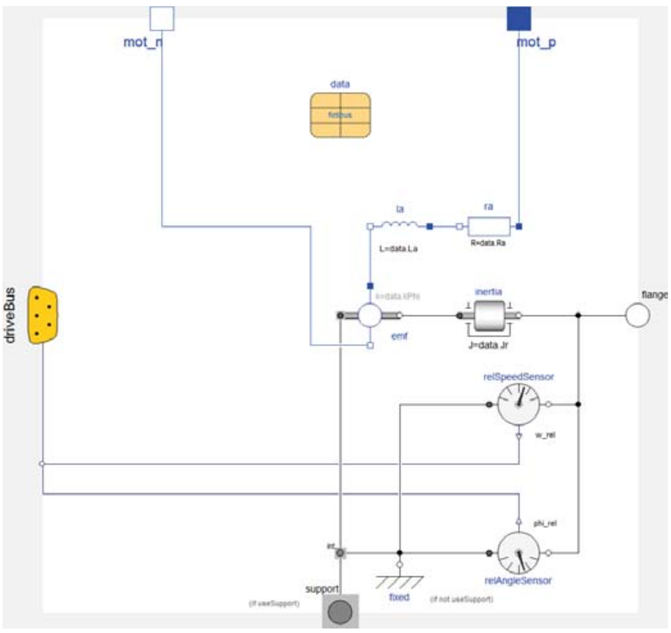
Drive

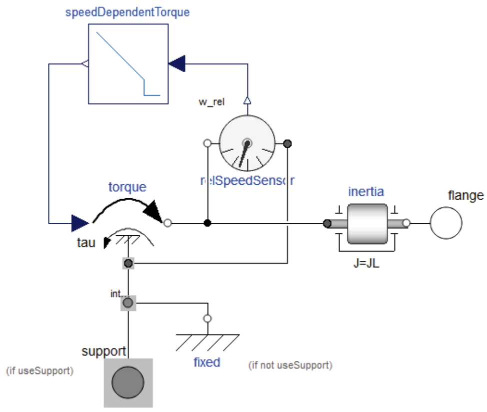
Drive = Machine + Inverter
(voltage source with dead-time)

- Dead time approximated by first order
- Measurements
- Communication: drive bus
- Parameterization: data record

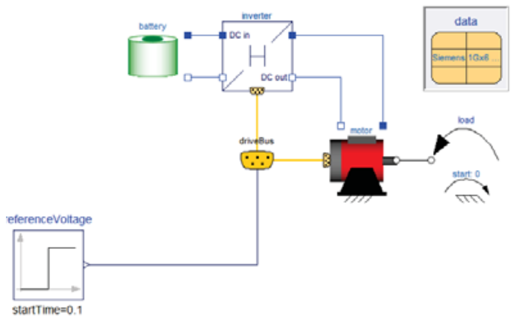


Load

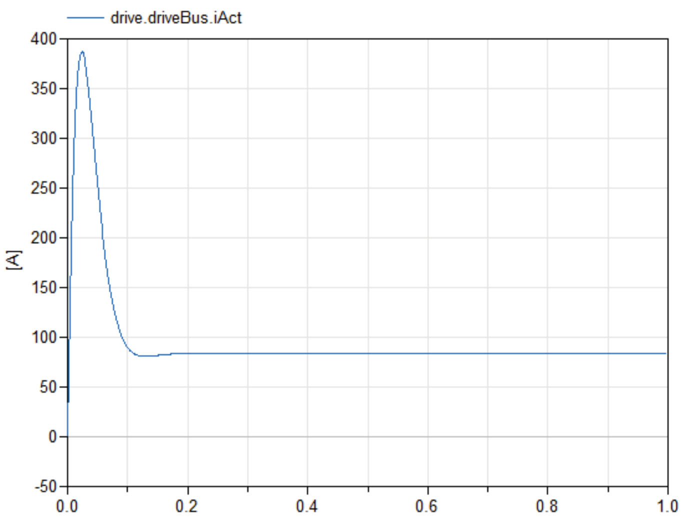
- Inertia
- Linear speed dependent torque
- Switched on at startTime



Test the Drive (without Control)



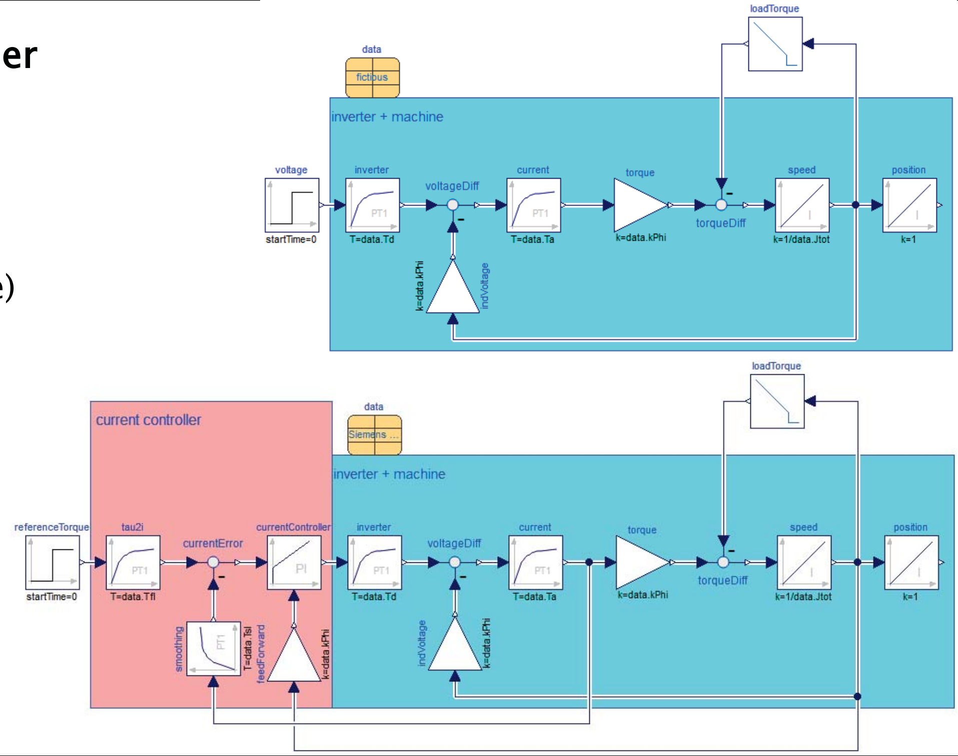
Hands-On: Example VoltageSupplied



stopTime=1.0, IntervalLength=0.001
referenceVoltage.height=data.VNom

Current Controller

- Take care of current filter (current ripple)



Current Controller

$$\frac{I_{Act,s}}{V_{Ref}} = G_D G_S = \frac{1}{(1+sT_d)} \cdot \frac{1}{R_A} \cdot \frac{1}{(1+sT_A)} \cdot \frac{1}{(1+sT_{sI})} = \frac{1}{R_A} \cdot \frac{1}{(1+sT_\sigma)(1+sT_A)}$$

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

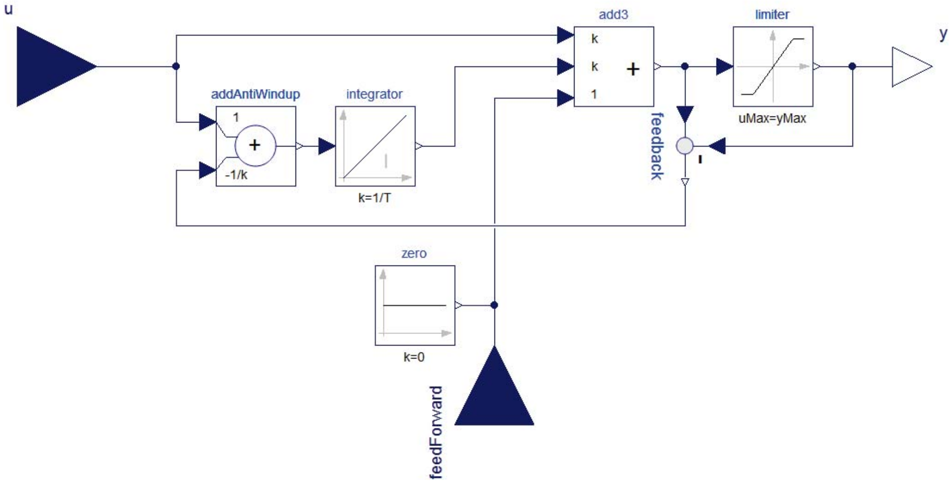
PI-controller

$$G_C = \frac{V_{Ref}}{I_{Err}} = k_{pI} \frac{1+sT_{iI}}{sT_{iI}}$$

- Feed-forward of $V_i = k \cdot \Phi \cdot \omega$
- Limit the output voltage → 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



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Parameterization of the Current Controller

$$G_o = G_C G_D G_S = \frac{k_{pI}}{R_A} \cdot \frac{1 + sT_{iI}}{sT_{iI}(1 + sT_\sigma)(1 + sT_A)}$$

Compensate the larger time constant →

$$T_{iI} = T_A = \frac{L_A}{R_A}$$

- Goal: smooth command action → absolute optimum

$$\left|\frac{I_{Act}}{I_{Ref,S}}\right| = \left|\frac{G_C G_D G_S}{1 + G_C G_D G_S}\right| = 1$$

Proportional Gain of the Current Controller

$$G(s) = \frac{G_0}{1+G_0} = \frac{1}{1+\frac{R_A}{k_{pI}} sT_A(1+sT_\sigma)} \xrightarrow{s=j\omega} \frac{1}{1-\omega^2 \frac{R_A}{k_{pI}} T_A T_\sigma + j\omega \frac{R_A}{k_{pI}} T_A}$$

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

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

Resulting Command Action of the Current Controlled Drive

$$\frac{I_{Act}}{I_{Ref}} = \frac{I_{Act,s}}{I_{Ref}} \cdot \frac{1}{G_S} = \frac{1+sT_{sI}}{1+s2T_\sigma + s^2 2T_\sigma^2}$$

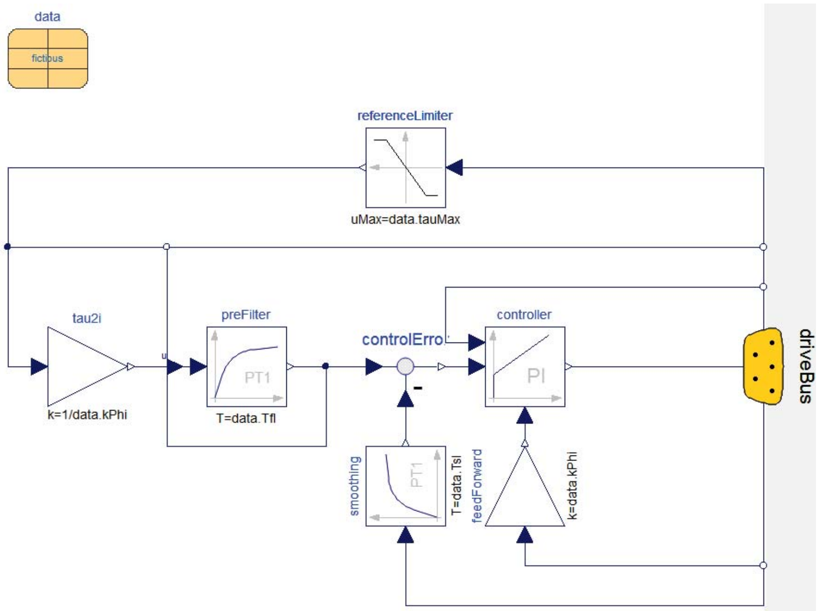
Compensate the numerator‘s zero with a first-order pre-filter.

$$\frac{\tau_{Act}}{\tau_{Ref}} = \frac{I_{Act}}{I_{Ref}} = \frac{1}{1+s2T_\sigma + s^2 2T_\sigma^2} \cong \frac{1}{1+sT_{sub}}$$

$$T_{sub} = 2T_\sigma$$

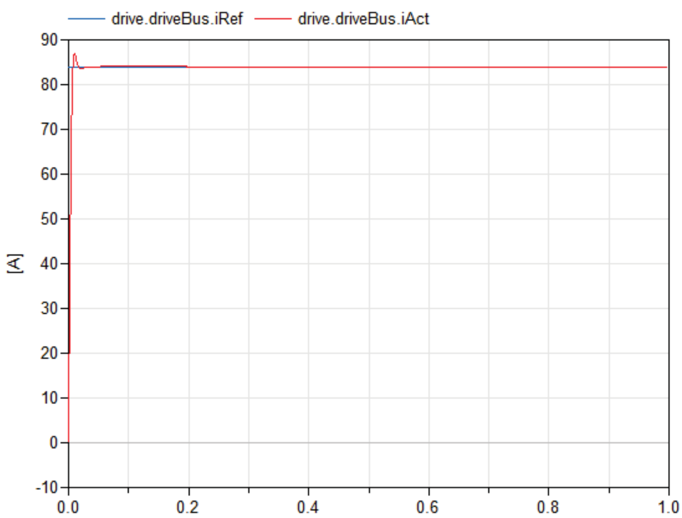
Current Controller

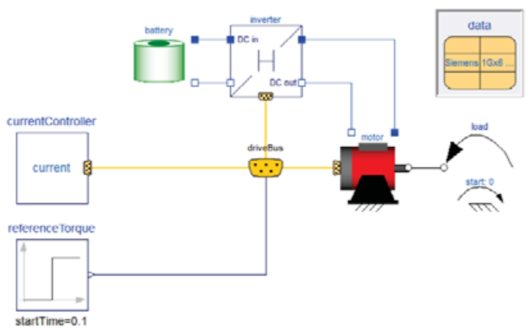
- Parameters calculated in the data record



Test the Current Controlled Drive

Hands-On: Example CurrentControlled





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

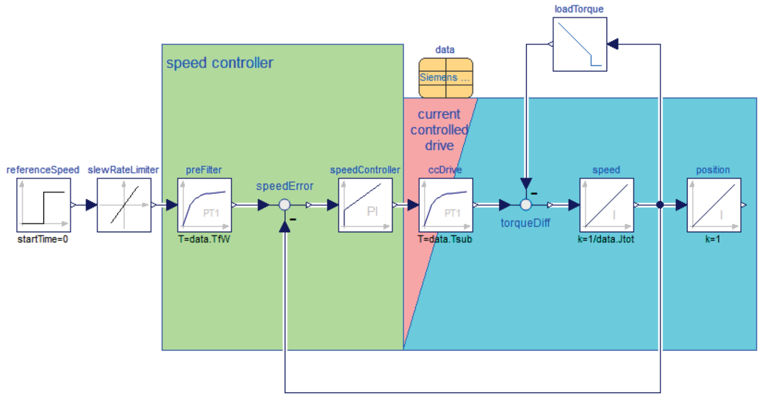
Speed Control

System under control=current controlled drive + speed integrator

$$G_D = \frac{\omega_{Act}}{\tau_{Ref}} = \frac{\tau_{Act}}{\tau_{Ref}} \cdot \frac{1}{sJ_{tot}} = \frac{1}{1+sT_{sub}} \cdot \frac{1}{sJ_{tot}} = \frac{\omega_N}{\tau_N} \cdot \frac{1}{sT_m(1+sT_{sub})}$$

Mechanical time constant

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



Speed Controller

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

$$G_C = k_{p\omega}\frac{1+sT_{i\omega}}{sT_{i\omega}}$$

$$G_o = G_C G_D = k_{p\omega}\frac{1+sT_{i\omega}}{sT_{i\omega}} \cdot \frac{\omega_N}{\tau_N} \cdot \frac{1}{sT_m(1+sT_{sub})}$$

Parameterization of the Speed Controller

Goal: compensation of disturbance ➔ symmetrical optimum

- Stability according to Nyquist:

$$arg(G_0) = -\pi + arctan(\omega_D T_{i\omega}) - arctan(\omega_D T_{sub}) > -\pi$$

- 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

$$arg(G_0) \rightarrow max: \frac{d[arg(G_0)]}{d\omega} = \frac{T_{i\omega}}{1+(\omega_D T_i)^2} - \frac{T_{ers}}{1+(\omega_D T_{sub})^2} = 0 \rightarrow \omega_D = \frac{1}{\sqrt{T_{i\omega} T_{sub}}}$$

Parameterization of the Speed Controller

$$T_{i\omega} = a^2 \cdot T_{sub} \rightarrow \omega_D = \frac{1}{a \cdot T_{sub}} = \frac{a}{T_{i\omega}} \rightarrow T_{i\omega} = a^2 \cdot T_{sub}$$

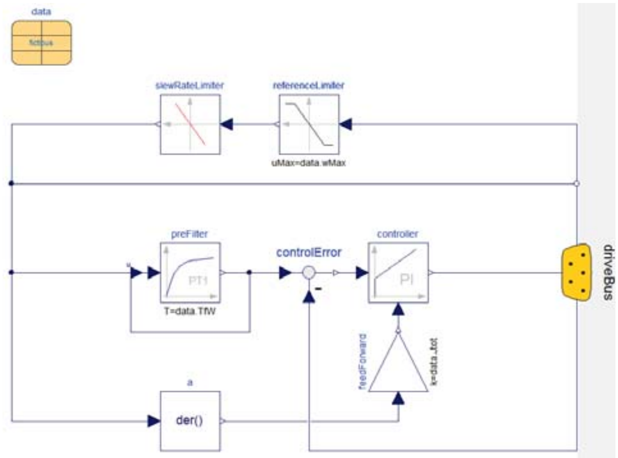
$$|G_0(j\omega_D)| = k_{p\omega} \cdot \frac{\omega_N}{M_N} \cdot \frac{aT_{sub}}{T_m} = 1 \rightarrow k_{p\omega} = \frac{M_N}{\omega_N} \cdot \frac{T_m}{aT_{sub}} = \frac{J_{tot}}{aT_{sub}}$$

$$G_0 = G_C G_D = \frac{1 + sa^2 T_{sub}}{s^2 a^3 T_{sub}^2 (1 + sT_{sub})}$$

$$\frac{\omega_{Act}}{\omega_{Ref}} = \frac{G_C G_D}{1 + G_C G_D} = \frac{1 + sa^2 T_{sub}}{1 + sa^2 T_{sub} + s^2 a^3 T_{sub}^2 + s^3 a^3 T_{sub}^3}$$

Compensate the numerator‘s zero with a first-order pre-filter.

Speed Controller



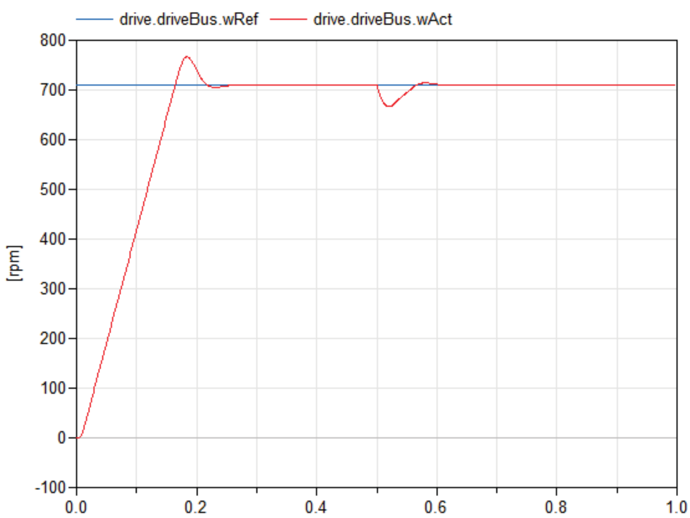
$$\frac{\omega_{Act}}{\omega_{Ref}} = G_F \cdot \frac{G_C G_D}{1 + G_C G_D} = \frac{1}{1 + s4T_{sub} + s^2 8T_{sub}^2 + s^3 8T_{sub}^3} \approx \frac{1}{1 + s4T_{sub}}$$

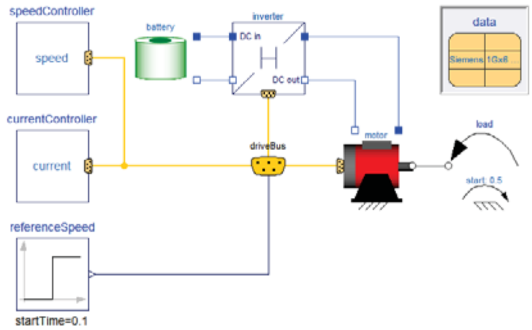
→ Filter reference speed with by „ramping“ (SlewRateLimiter),

i.e. limit necessary torque for acceleration / deceleration

Test the Speed Controlled Drive

Hands-On: Example SpeedControlled





stopTime=1.0, IntervalLength=0.001

referenceSpeed.height=data.wNom

slewRateLimiter.{Rising=data.aMax,
initType=initialOutput, y_start=referenceSpeed.offset}

currentController.data=data

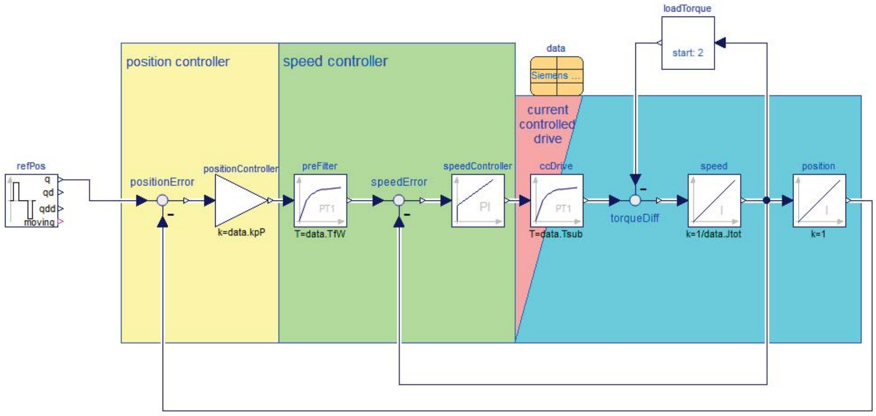
speedController.data=data

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

→ P-controller is sufficient

$$\frac{\varphi_{Act}}{\varphi_{Ref}} = \frac{G_C G_D}{1 + G_C G_D} = \frac{1}{1 + s\frac{1}{k_{pP}} + s^2\frac{4T_{sub}}{k_{pP}}} = \frac{1}{1 + 2\vartheta Ts + (sT)^2}$$

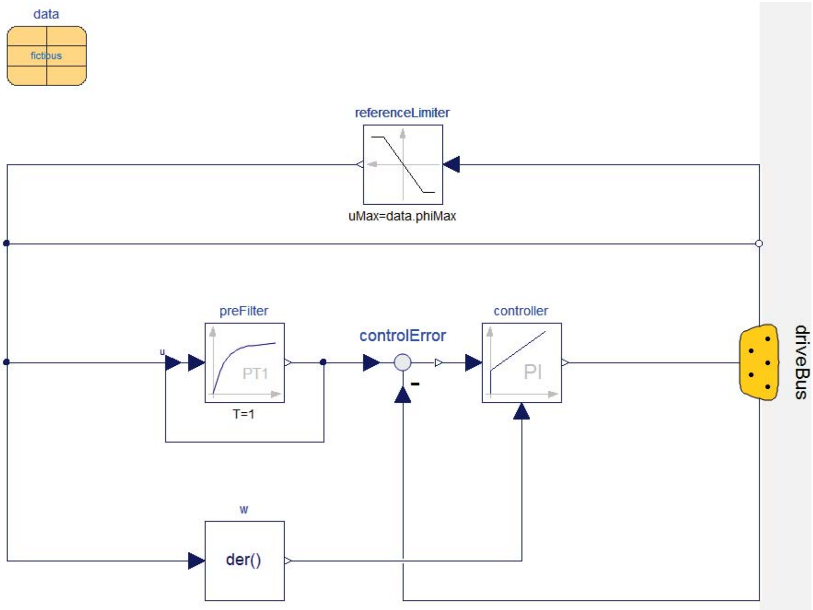
Avoid overshot over reference end position →

$$\vartheta = \frac{1}{\sqrt{16k_{pP}T_{sub}}} \geq 1 \; \rightarrow \; k_{pP} \leq \frac{1}{16T_{sub}}$$

Position Controller

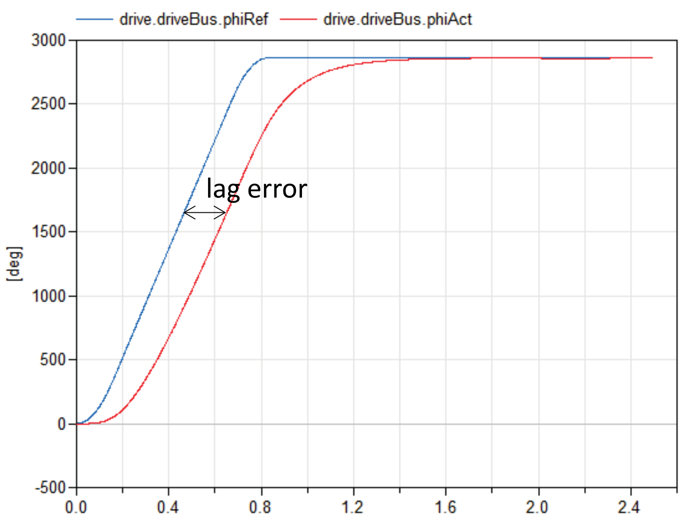
Reference position limits:
Modelica.Blocks.Sources.
KinematicPTP2

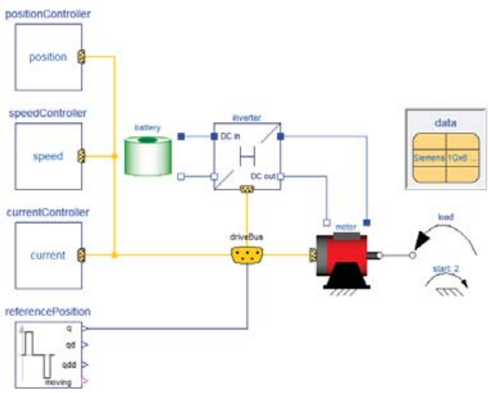
- Speed limit $\rightarrow \frac{d\varphi}{dt}$
- Torque limit $\rightarrow \frac{d^2\varphi}{dt^2}$



Test the Position Controlled Drive

Hands-On: Example PositionControlled





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 → field weakening

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

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

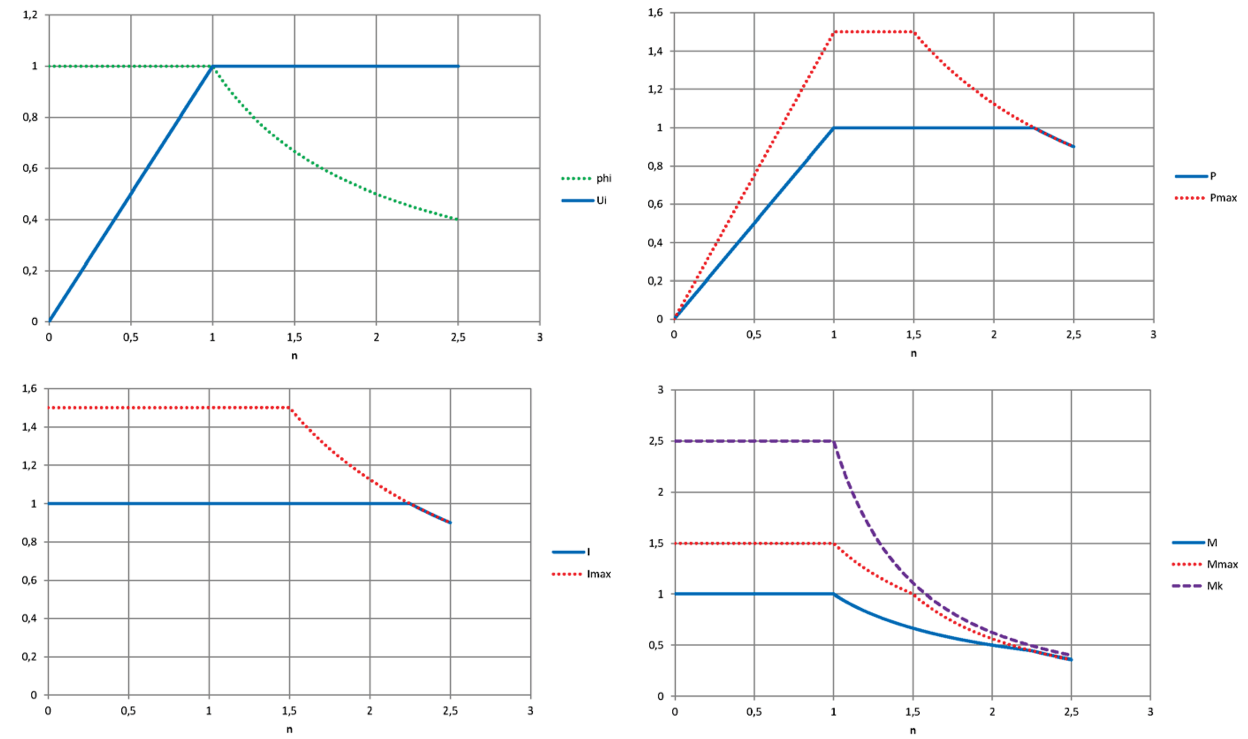
- Some adaptions in controllers due to $\Phi \sim \frac{1}{n}$.

Field Weakening

Base speed region	Field weakening
$\phi = const.$	$\phi \sim \frac{1}{\omega}$
$V \sim \omega$	$V = const.$
$I = const.$	$I = const.$
$\tau = const.$	$\tau \sim \frac{1}{\omega}$
$P \sim \omega$	$P = const.$

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

Maximum torque of the machine $\tau_{Break\ Down} \sim \Phi^2$



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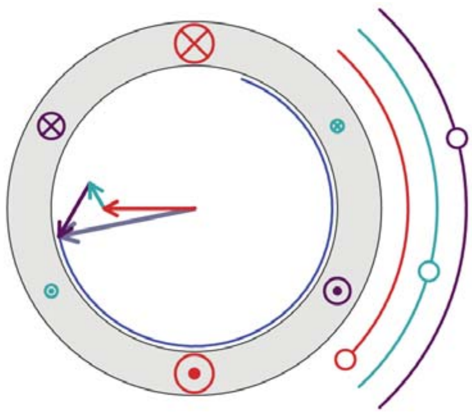
Field Oriented Control (FOC)

- Based on space phasors:

$\underline{i} = \frac{2}{3}\left(i_a + \underline{a} \cdot i_b + \underline{a}^2 \cdot i_c\right)$

→ 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!

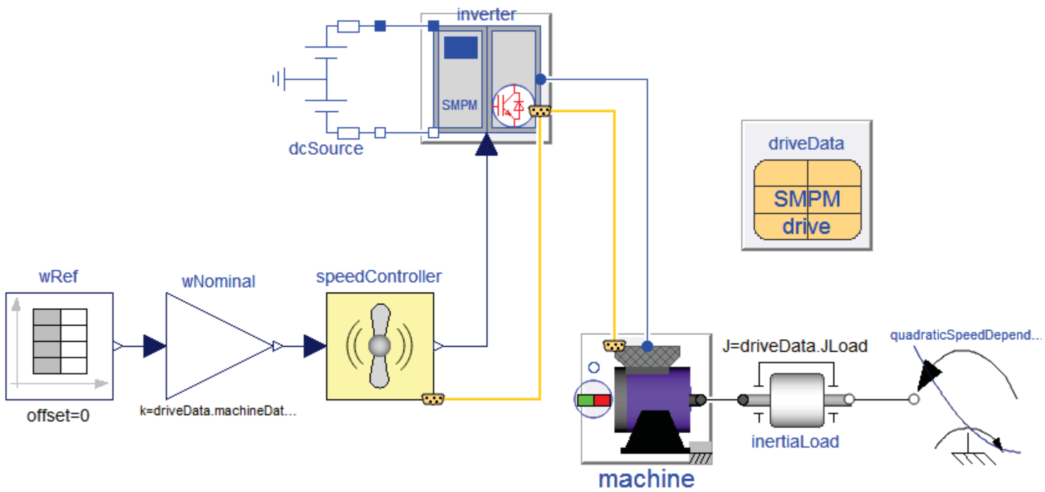
EDrives Library

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

EDrives Library



Contact: http://www.ltx.de/english.html

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References

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Thank you for your attention!

Any questions?

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