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Simulation of Electric Drives using the Machines Library and the SmartElectricDrives Library

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arsenal research, Vienna
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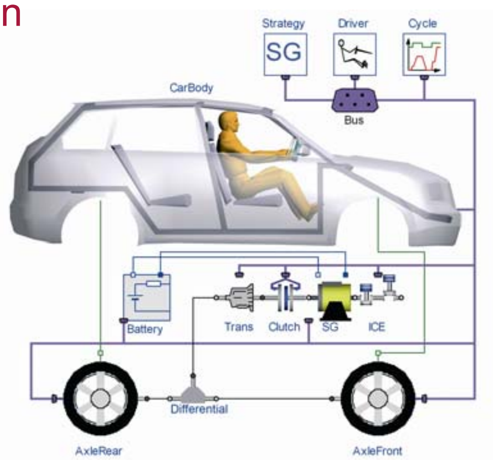
Contents

The SmartElectricDrives Library - Introduction

Chapter 1



Overview

- Major components of the SED library
  - Asynchronous induction machines, permanent magnet synchronous induction machines, dc machines
  - Field oriented control, brushless dc control
  - Converters (ideal, switching), sources (batteries, supercaps, fuel cells)
- Application examples
  - Hybrid electric vehicles (HEVs), electric vehicles (EVs)
  - Starter / generator, electrically operated auxiliaries
  - Machine-tools and robotics
  - Paper mills, mining
  - Construction machinery, assembly lines
  - etc.

Application Specific Drive Design I

Practical Considerations

- Various technologies (e.g. batteries, supercaps, fuel cells etc.)
- Matching the right components based on their specifications
- Maximizing the efficiency of the entire drive system
- Comprehensive analysis of dynamic effects
- Component security (currents, voltages, etc.)
- Controller calibration (dynamic characteristics and static characteristics)

Application Specific Drive Design II

Software Requirements

- Hybrid systems
  - Simulation of mechanical and electrical components at the same time
  - User friendliness
- High processing effort
  - Definition of different layers of abstraction
- Short development cycles
  - Automation of development procedures with ‘Ready to use’ - models

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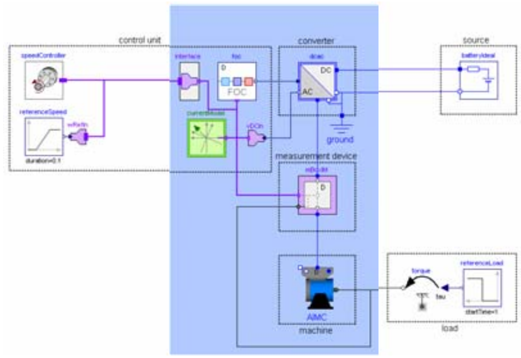
Components of Electric Drives

- Sources
- Converters
- Electric machines
- Measurement devices
- Control units
- Mechanical loads



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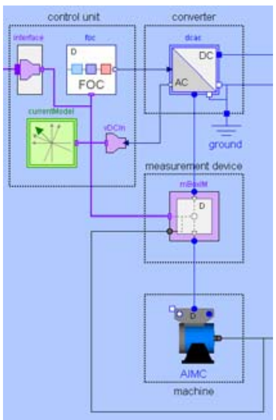
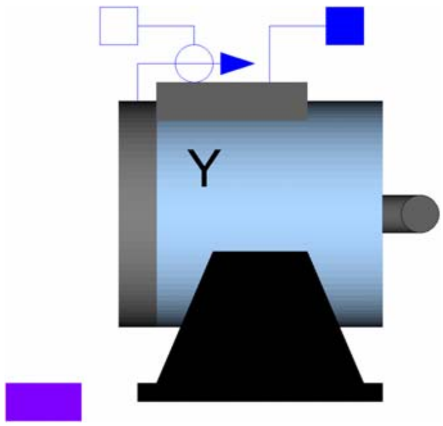
‘Ready to use’ Models





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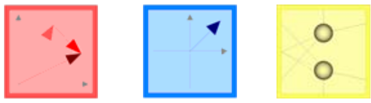
‘Ready to use’ Models

- Models of controlled machines

- Models of drive controllers

- Models of elementary controllers



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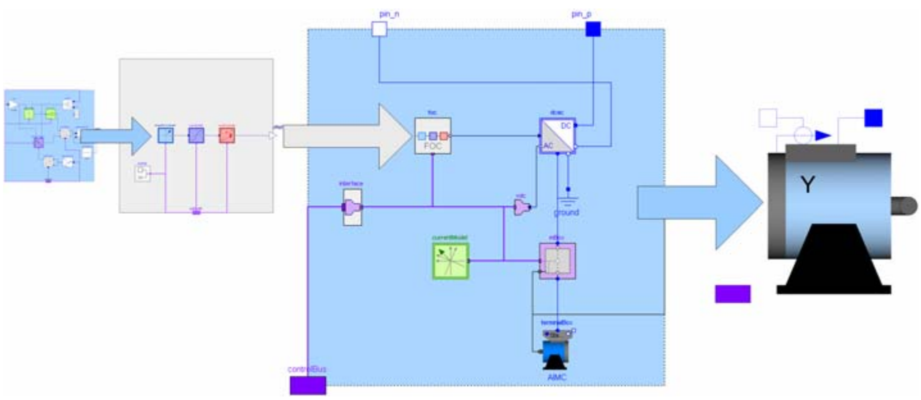
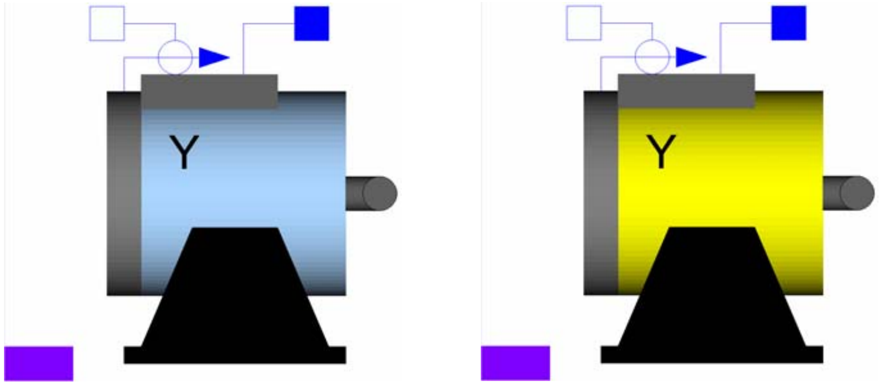
Torque Controlled Induction Machine with Integrated Converter



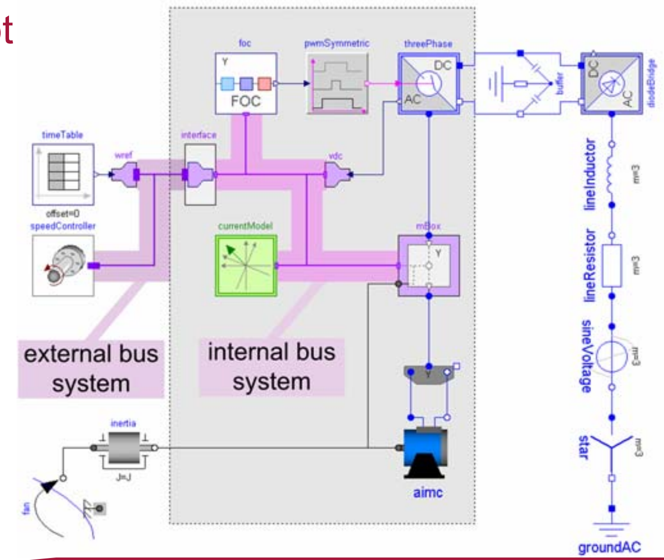
Connectors of the Controlled Machine Models



Different Levels of Abstraction

Models of controlled machines	Electrical transients and mechanical transients	
	Quasi stationary models (only mechanical transients)	
Converters	Power balance	
	Ideal switches	 

Bus Concept



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Key Advantages of the SED library

- Comprehensive library for electric drive simulation in automotive applications
- Applicable for hardware in the loop (HIL) and real time simulations
- ‘Ready to use’ models
- Controller parameter estimation functions for easy controller handling
- Models at different layers of abstraction
- SED bus concept for easy coupling with other Dymola libraries
- Many examples, extensive documentation and intelligible SED library structure

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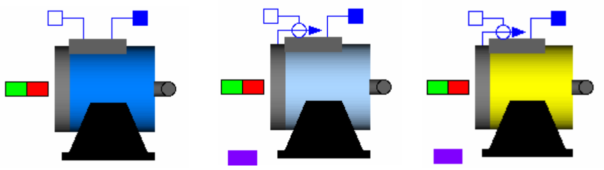
DC Machines

Chapter 2



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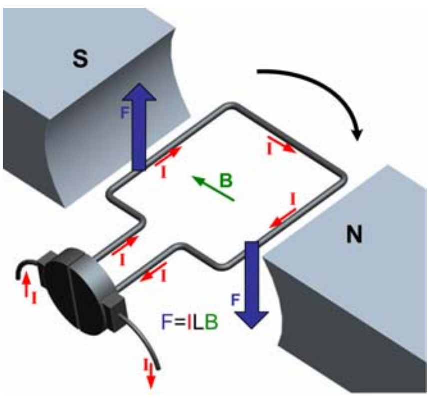
Principle

- The stator magnet creates a homogeneous magnetic field
- Opposite current direction in the proximity of the poles
- Same torque at all wires in the armature
- Commutator works as a mechanical rectifier



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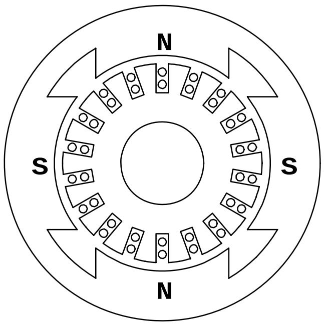
Torque and Power

- Armature current I_a
- Main flux Φ
- Induced voltage
  $V_i = k \cdot \Phi \cdot \Omega_m$
- Torque
  $T = k \cdot \Phi \cdot I_a$
- Mechanical power
  $P_m = V_i \cdot I_a = T_{el} \cdot \Omega_m$



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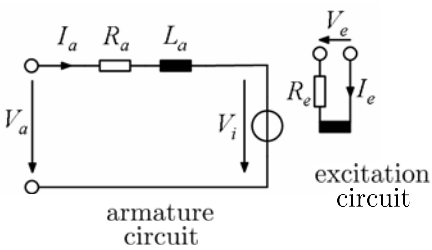
DC Drive Turn-on

- Excitation winding (switch on separate excitation first)
- Maximum turn-on current
  - $I_a \leq \frac{V_a}{R_a}$
- Turn-on current limitation
  - Starter resistors
  - Variable armature voltage



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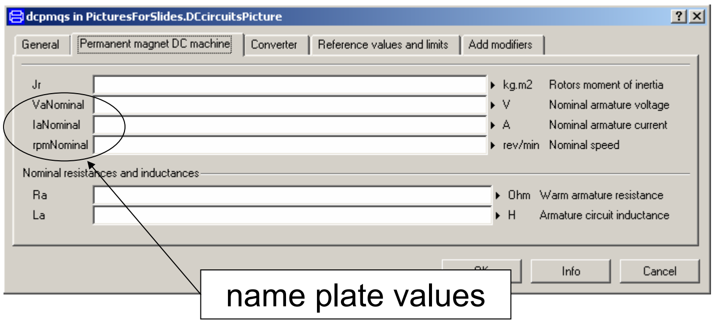
Parameter List of the DCPM – Machine Model



Chapter 2: DC Machines

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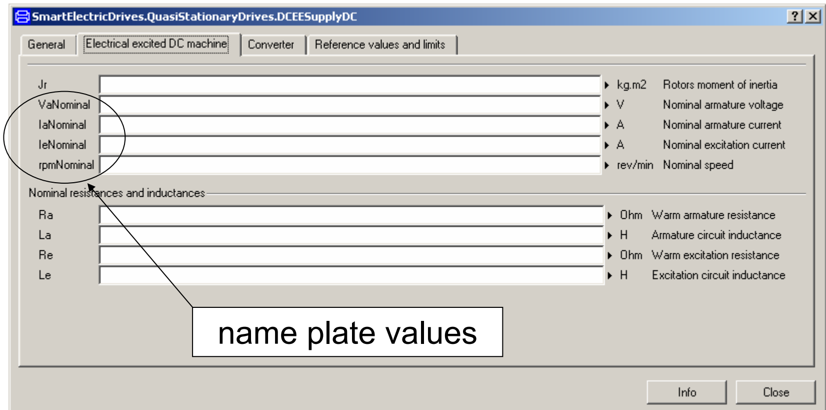
Parameter List of the DCEE – Machine Model



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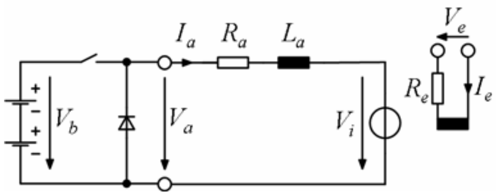
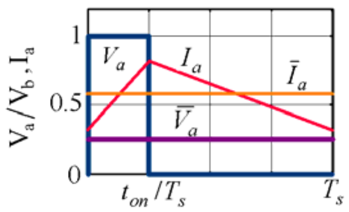
Chopper

- DC supply
- Step down converter
  - $V_a = D \cdot V_s$
  - $D = \frac{t_{on}}{T_s}$
- Electric switches
- Free wheeling diode





T_s:...switching periode

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Chopper Models in the SED Library

- Power balance model
  - Low computing effort

- Ideal switching model
  - Events
  - Iteration
  - Computing effort dependent on switching frequency

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Examples with a Chopper and a DC Machine

Exercise 1

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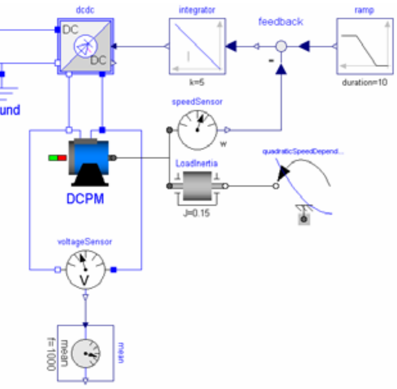
SED Example – Chopper01

- Given:
  - Battery voltage = 100V
  - Reference speed:

$$\frac{dn}{dt} = \frac{1425rpm}{10s} \quad n_{Max} = n_{Nominal}$$

  - Chopper frequency = 1000Hz
- Display: $i_a(t)$, $v_a(t)$, $\overline{I}_a$, $\overline{V}_a$, ω_m
  - Change the integrator gain



Chopper01: Component Paths

- SmartElectricDrives.Sources.Batteries.BatteryIdeal
- Modelica.Electrical.Analog.Basic.Ground
- SmartElectricDrives.Converters.IdealSwitching.DCDC.Chopper
- Modelica.Blocks.Continuous.Integrator
- Modelica.Blocks.Math.Feedback
- Modelica.Blocks.Sources.Ramp
- Modelica.Mechanics.Rotational.Sensors.SpeedSensor
- Modelica.Electrical.Machines.BasicMachines.DCMachines. DC_PermanentMagnet
- Modelica.Mechanics.Rotational.Inertia
- Modelica.Mechanics.Rotational.QuadraticSpeedDependentTorque
- Modelica.Electrical.Analog.Sensors.VoltageSensor
- SmartElectricDrives.Sensors.Mean

Chopper01: Parameter Settings

- BatteryIdeal
  - VCellNominal = 100V
  - ICellMax = 150A
  - RsCell = 0Ω
  - ns = 1
  - np = 1
- Chopper
  - f = 1000Hz
  - IConverterMax = 150A
  - VDC = 100V
- Integrator
  - k = 5
- Ramp
  - height = 149
  - duration = 10s
- DCPM
  - Nominal values
- Inertia
  - J = 0.15kgm^2

Chopper01: Parameter Settings

- QuadraticSpeedDependentTorque
  - tau_Nominal = -63.66Nm
  - w_Nominal = 149 rad^-1
- Mean
  - f = 1000Hz
  - yStart = 0
- Simulation time
  - t = 15s

Chopper01: System Analyses

- Integrator gain changed; k = 1,
  - **Compare:** DCPM.w_mechanical, DCPM.ia, dcdc.vRef
  - The armature current decreases
  - The shaft acceleration is delayed
  - The reference voltage raise is delayed
- Ramp duration changed; t = 2s,
  - The shaft acceleration increases
  - The armature current increases

Exercise 1: **Examples with a Chopper and a DC Machine**

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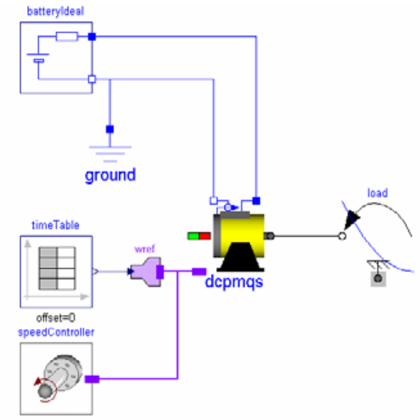
SED Example – DCPMQS01

- DCPM Water pump drive
  - Battery voltage = 120V
  - Speed controlled
- Display: $i_a(t),\ v_a(t),\ \omega_m,\ \omega_{ref}$
  - Check current limits
  - Check voltage limits
  - Check Torque limit



Exercise 1: **Examples with a Chopper and a DC Machine**

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DCPMQS01: Component Paths

- SmartElectricDrives.Sources.Batteries.BatteryIdeal
- Modelica.Electrical.Analog.Basic.Ground
- Modelica.Blocks.Sources.Ramp
- Modelica.Blocks.Sources.TimeTable
- SmartElectricDrives.Interfaces.BusAdaptors.WRefIn
- SmartElectricDrives.QuasiStationaryDrives.DCPMSupplyDC
- Modelica.Mechanics.Rotational.QuadraticSpeedDependentTorque
- SmartElectricDrives.ProcessControllers.SpeedController
- SmartElectricDrives.AuxiliaryComponents.Functions.parameterEstimationDCPMControllers

DCPMQS01: Parameter Settings

- BatteryIdeal
  - VCellNominal = 1.5V
  - ICellMax = 400A
  - RsCell = 0.004Ω
  - ns = 80
  - np = 2
- DCPMQS
  - Jr = 0.15 kgm^2
  - VaNominal = 100V
  - IaNominal = 100A
  - rpmNominal = 1425rpm
  - (wNominal = 149s^-1)
  - (TauNominal = 63.66Nm)
  - Ra = 0.05Ω
  - La = 0.0015Ω
  - TiConverter = 0.001s
  - vMachineMax = 1.1 VaNominal
  - iMachineMax = 1.5 IaNominal
  - IConverterMax = 2.5 IaNominal

Exercise 1: Examples with a Chopper and a DC Machine

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DCPMQS01: Parameter Settings

- TimeTable
  - table=[0, 0; 0, 0; 0.2, wNominal/2;1, wNominal/2; 1.2, wNominal; 2, wNominal]
- QuadraticSpeedDependentTorque
  - tau_Nominal = -63.66Nm
  - w_Nominal = 149 rad^-1
- parameterEstimationDCPMControllers
  - kdynaCurrent = 5
  - kdynSpeed = 1
- Speed Controller
  - kpSpeed = 29.3
  - TiSpeed = 0.024s
  - TauMax = 1.2 tau_nominal = 76Nm
- Simulation time
  - t = 2s

Exercise 1: Examples with a Chopper and a DC Machine

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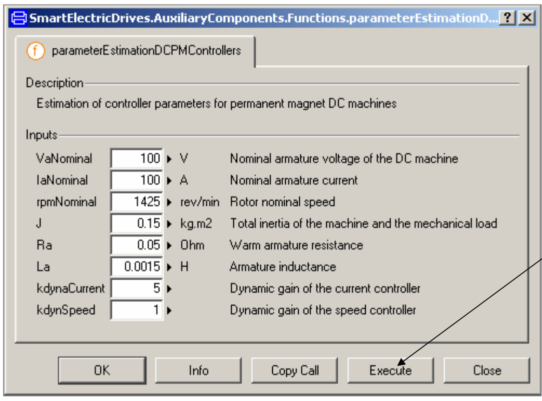
Using the Parameter Estimation Function

- parameterEstimationDCPMControllers



Generate controller settings

Exercise 1: Examples with a Chopper and a DC Machine

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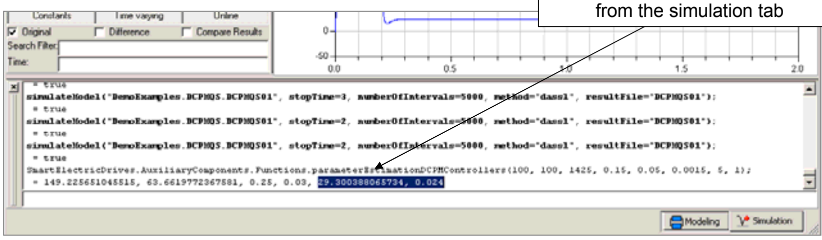
Using the Parameter Estimation Function

- parameterEstimationDCPMControllers(VaNominal, IaNominal, rpmNominal, J, Ra, La, kdynaCurrent, kdynSpeed) = wNominal, tauNominal, kpaCurrent, TiaCurrent, kpSpeed, TiSpeed

Retrieve the controller settings from the simulation tab



Exercise 1: Examples with a Chopper and a DC Machine

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DCPMQS01: System Analyses

- The machine does not reach the desired acceleration close to w_Nominal.
  - **Display from dcpmqs.controlBus:** vMachine, vMachineMax, vDC, iMachine, iMachineMax, wMechanical, wRef, TauRef
  - **Display furthermore:** speedController.TauMax
  - The torque limit TauMax is too low.
  - Increase TauMax

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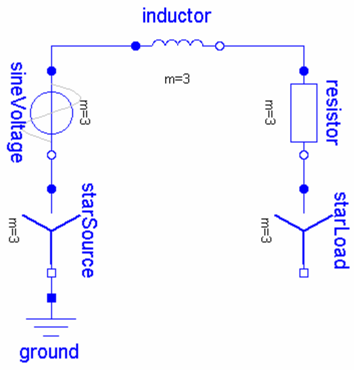
AC Circuits

Chapter 3



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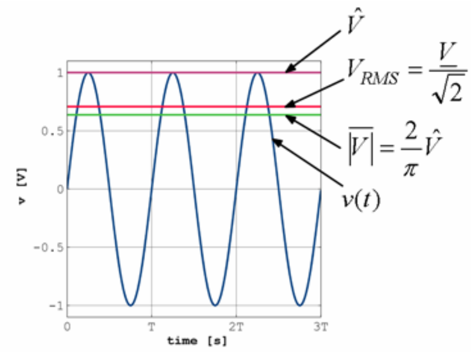
AC Signal Values



- Mean value
  - $\overline{V} = 0$
- RMS value
  - $V_{RMS} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt}$
- Rectified mean value
  - $\overline{|V|} = \frac{1}{T}\int_0^T |v(t)|\, dt$
- Peak value
  - $v(t)|_{\omega t = \frac{\pi}{2}} = \hat{V} = \hat{V} \cdot sin(\omega t)$

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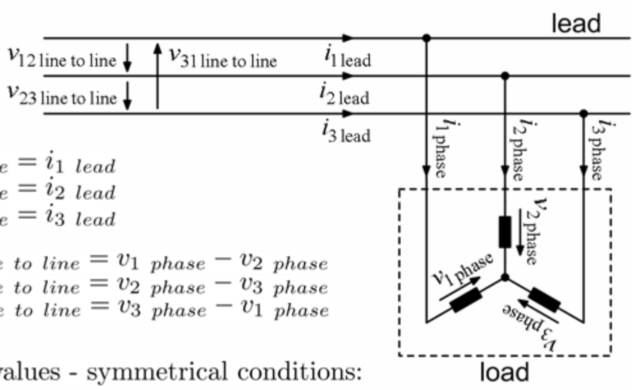
Three Phase Star Connection



$i_{1\ phase} = i_{1\ lead}$
$i_{2\ phase} = i_{2\ lead}$
$i_{3\ phase} = i_{3\ lead}$

$v_{12\ line\ to\ line} = v_{1\ phase} - v_{2\ phase}$
$v_{23\ line\ to\ line} = v_{2\ phase} - v_{3\ phase}$
$v_{31\ line\ to\ line} = v_{3\ phase} - v_{1\ phase}$

RMS values - symmetrical conditions:

$V_{line\ to\ line} = \sqrt{3} \cdot V_{phase}$

$I_{lead} = I_{phase}$

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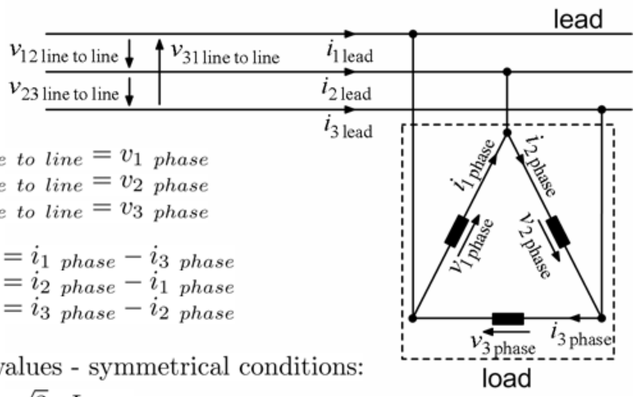
Three Phase Delta Connection



$v_{12\ line\ to\ line} = v_{1\ phase}$
$v_{23\ line\ to\ line} = v_{2\ phase}$
$v_{31\ line\ to\ line} = v_{3\ phase}$

$i_{1\ lead} = i_{1\ phase} - i_{3\ phase}$
$i_{2\ lead} = i_{2\ phase} - i_{1\ phase}$
$i_{3\ lead} = i_{3\ phase} - i_{2\ phase}$

RMS values - symmetrical conditions:

$I_{lead} = \sqrt{3} \cdot I_{phase}$
$V_{line\ to\ line} = V_{phase}$

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Name Plate Excerpts

$9.11V \cdot \frac{1}{\sqrt{3}} = 5.26V$

Name plate design 1:

p	=	2		
$f_{Nominal}$	=	130	Hz	
V_0	=	9.11	V	Y
$I_{Nominal}$	=	12.7	A	Y

Phase values

$22A \cdot \frac{1}{\sqrt{3}} = 12.7A$

Name plate design 2:

p	=	2		
$f_{Nominal}$	=	130	Hz	
V_0	=	5.26	V	Δ
$I_{Nominal}$	=	22	A	Δ

Phase values

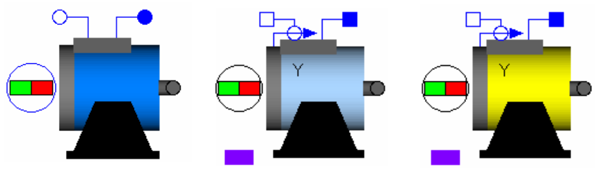
Name plate design 3:

p	=	2		
$f_{Nominal}$	=	130	Hz	
V_0	=	9.11 / 5.26	V	Y / Δ
$I_{Nominal}$	=	12.7 / 22	A	Y / Δ

Phase values

Permanent Magnet Synchronous Induction Machines

Chapter 4



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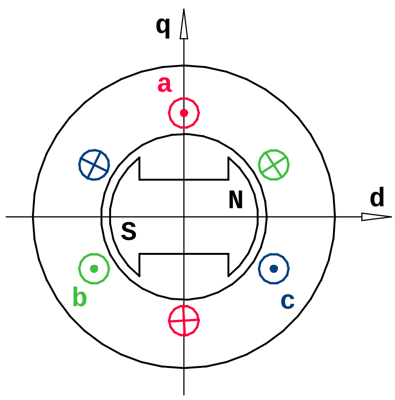
Principle Assembly

- Stator winding
  - Three phases
  - Symmetrical
- Pole wheel
  - Permanent magnets
  - Approximately sinusoidal field distribution



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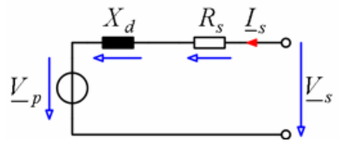
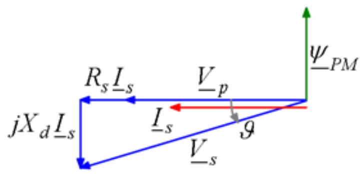
Equivalent Circuit

- Magnetically symmetric





- Synchronous d-reactance
  - $X_d = X_{dm} + X_\sigma$

$$\underline{V}_s = R_s\underline{I}_s + jX_d\underline{I}_s + \underline{V}_p$$
$$\underline{V}_p = j\Omega\underline{\Psi}_{PM}$$

- Stator stray reactance
  - X_σ
- Load angle
  - ϑ

- Field Oriented Control (FOC)

$I_{s,q} \perp \psi_{PM} \Rightarrow T_{electric}$

$I_{s,d} \; // \; \psi_{PM} \Rightarrow \text{Field Weakening}$

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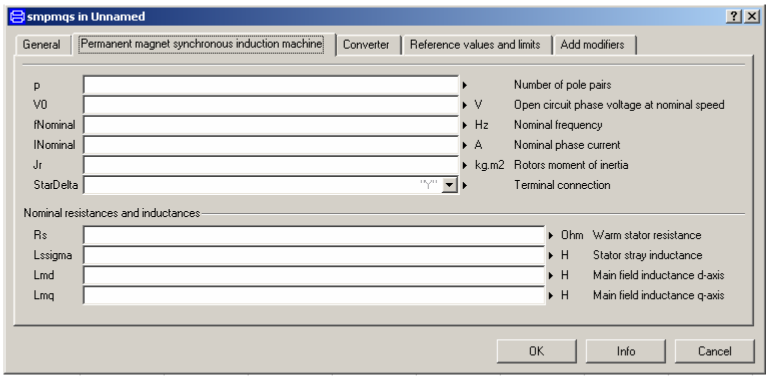
Parameter List of the PMSM Model



Finding the nominal shaft speed

- Example1: PMSM $n_{Nominal} = 1500\text{rpm},\ p = 2$

$$\Omega_{m,Nominal} = \frac{2\pi}{60} n_{Nominal} = 157\frac{rad}{s}$$

$$\omega_{el,Nominal} = \Omega_{m,Nominal} \cdot p = 314\frac{rad}{s} \Rightarrow f_{Nominal} = \frac{\omega_{el,Nominal}}{2\pi} = 50\text{Hz}$$

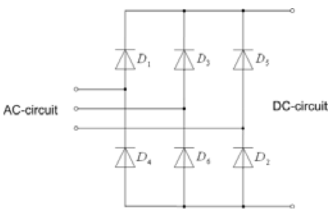
- Example2: PMSM $f_{Nominal} = 120\text{Hz},\ p = 4$

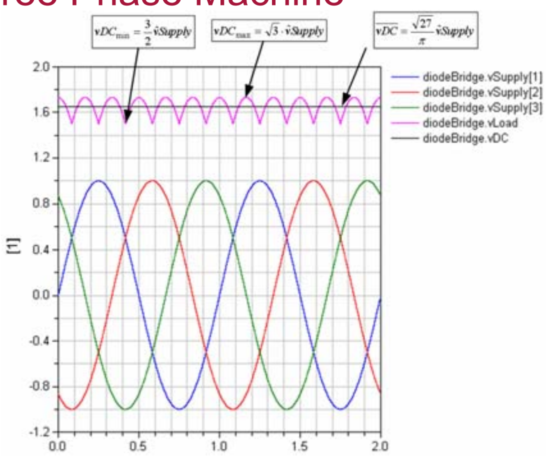
$$\omega_{el,Nominal} = f_{Nominal} \cdot 2\pi = 754\frac{rad}{s}$$

$$\Omega_{m,Nominal} = \frac{\omega_{el,Nominal}}{p} = 188\frac{rad}{s} \Rightarrow n_{Nominal} = 1800\text{rpm}$$

Converter Fed Three Phase Machine

- DC-link voltage limits
  - Example:
  - 6 pulse diode bridge





Example with a PM Synchronous Machine

Exercise 2

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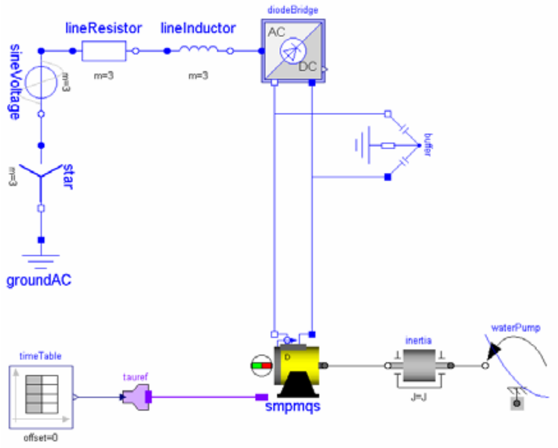
SED Example – SMPMQS01

- PMSM water pump drive
  - Three phase supply
  - Torque controlled
- Display:

  $i_s(t), v_s(t), \omega_m(t)$
  - Check current limits
  - Check voltage limits
  - Check control quality



SMPMQS01: Component Paths

- Modelica.Electrical.Analog.Basic.Ground
- Modelica.Electrical.MultiPhase.Basic.Star
- Modelica.Electrical.MultiPhase.Sources.SineVoltage
- Modelica.Electrical.MultiPhase.Basic.Resistor
- Modelica.Electrical.MultiPhase.Basic.Inductor
- SmartElectricDrives.Converters.IdealSwitching.ACDC.ThreePhaseDiodeBridge
- SmartElectricDrives.Converters.AuxiliaryComponents.BufferingCapacitor
- SmartElectricDrives.QuasiStationaryDrives.SMPMSupplyDC
- Modelica.Blocks.Sources.TimeTable
- SmartElectricDrives.Interfaces.BusAdaptors.TauRefIn
- Modelica.Mechanics.Rotational.Inertia
- Modelica.Mechanics.Rotational.QuadraticSpeedDependentTorque

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SMPMQS01: Parameter Settings

- SMPMQS
  - m = 3
  - p = 2
  - Jr = 0.29kgm^2
  - V0 = 112.3V
  - INominal = 100A
  - fNominal = 50Hz
  - (wNominal = 157s^-1)
  - (tauNominal = 214Nm)
  - (VNominal =122V)
- SMPMQS
  - Rs = 0.03Ω
  - Lssigma = 3.1847e-4H
  - Lmd = 9.549e-4H
  - Lmq = 9.549e-4H
  - Lrsigma = 1.5923e-4H
  - Rr = 0.04Ω
  - TiConverter = 0.001s
  - vMachineMax = VNominal
  - iMachineMax = INominal
  - IConverterMax = 400A

SMPMQS01: Parameter Settings

- AC supply grid
  - m = 3
  - V = 110V
  - frequHz = 50Hz
  - R = 1e-5Ω
  - L = 1e-4H
- Diode bridge
  - IConverterMax = 400A
  - f = 50Hz
- Buffer
  - C = 0.07F
  - R = 1e5Ω
  - V0 = 3 sqrt(3) 110V / pi
- TimeTable
  - table=[0,0; 0.1,0; 0.3,tauNominal/4; 0.5,tauNominal/4; 0.6,tauNominal; 0.8,tauNominal]
- QuadraticSpeedDependentTorque
  - tau_Nominal = -214Nm
  - w_Nominal = 157 rad^-1
- Inertia
  - J = 0.01kgm^2
  - t = 2s

SMPMQS01: System Analyses

- The electric torque of the machine follows the desired torque with satisfactory precision.
  - **Display from smpmqs.controlBus:** vMachine, vMachineMax, vDC, iMachine, iMachineMax, wMechanical, TauRef
  - **Display furthermore:** smpmqs.tauElectrical, smpmqs.isd, smpmqs.isq

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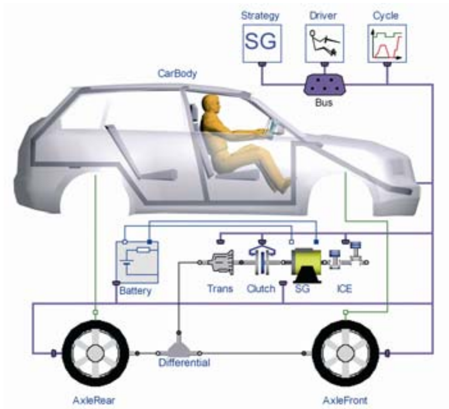

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Thanks for your time

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