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

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Chapter 1: The SmartElectricDrives Library - Introduction

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)

Chapter 1: The SmartElectricDrives library - Introduction

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
Components of Electric Drives

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

‘Ready to use’ Models
Chapter 1: The SmartElectricDrives library - Introduction

‘Ready to use’ Models

- Models of controlled machines
- Models of drive controllers
- Models of elementary controllers

Torque Controlled Induction Machine with Integrated Converter
Connectors of the Controlled Machine Models

Different Levels of Abstraction

<table>
<thead>
<tr>
<th>Models of controlled machines</th>
<th>Electrical transients and mechanical transients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi stationary models (only mechanical transients)</td>
<td></td>
</tr>
<tr>
<td>Converters</td>
<td>Power balance</td>
</tr>
<tr>
<td>Ideal switches</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 1: The SmartElectricDrives library - Introduction

Bus Concept

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
Chapter 2: DC Machines

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
Torque and Power

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

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
Parameter List of the DCPM – Machine Model

Parameter List of the DCEE – Machine Model
Chopper

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

$T_s$: switching period

Chopper Models in the SED Library

- Power balance model
  - Low computing effort

- Ideal switching model
  - Events
  - Iteration
  - Computing effort dependent on switching frequency
Examples with a Chopper and a DC Machine

Exercise 1

SED Example – Chopper01

• Given:
  – Battery voltage = 100V
  – Reference speed:
    \[ \frac{d\alpha}{dt} = \frac{1425 \text{ rpm}}{10 \text{s}} \]
    \[ n_{\text{Max}} = n_{\text{Nominal}} \]
  – Chopper frequency = 1000Hz
• Display: \( i_a(t) \), \( v_a(t) \), \( \overline{I}_a \), \( \overline{V}_a \), \( \omega_m \)
  – Change the integrator gain
Chopper01: Component Paths

- SmartElectricDrives.Sources.Batteries.BatteryIdeal
- SmartElectricDrives.Converters.IdealSwitching.DCDC.Chopper
- Modelica.Blocks.Sources.Ramp
- Modelica.Electrical.Machines.BasicMachines.DCMachines.DC_PermanentMagnet
- SmartElectricDrives.Sensors.Mean

Exercise 1: Examples with a Chopper and a DC Machine

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 = 0.15kgm²
Chopper01: Parameter Settings

- QuadraticSpeedDependentTorque
  - \( \tau_{\text{Nominal}} = -63.66 \text{Nm} \)
  - \( w_{\text{Nominal}} = 149 \text{ rad}^{-1} \)
- Mean
  - \( f = 1000 \text{Hz} \)
  - \( y_{\text{Start}} = 0 \)
- Simulation time
  - \( t = 15 \text{s} \)

Chopper01: System Analyses

- Integrator gain changed; \( k = 1 \),
  - \textbf{Compare}: DCPM.w_{\text{mechanical}}, DCPM.ia, dcdc.vRef
  - The armature current decreases
  - The shaft acceleration is delayed
  - The reference voltage raise is delayed
- Ramp duration changed; \( t = 2 \text{s} \),
  - The shaft acceleration increases
  - The armature current increases
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

DCPMQS01: Component Paths

- SmartElectricDrives.Sources.Batteries.BatteryIdeal
- Modelica.Blocks.Sources.Ramp
- Modelica.Blocks.Sources.TimeTable
- SmartElectricDrives.Interfaces.BusAdaptors.WRefIn
- SmartElectricDrives.QuasiStationaryDrives.DCPMSupplyDC
- SmartElectricDrives.ProcessControllers.SpeedController
- SmartElectricDrives.AuxiliaryComponents.Functions.parameterEstimationDCPMControllers
Exercise 1: Examples with a Chopper and a DC Machine

DCPMQS01: Parameter Settings

**BatteryIdeal**
- VCellNominal = 1.5V
- ICellMax = 400A
- RsCell = 0.004Ω
- ns = 80
- np = 2

**DCPMQS**
- Jr = 0.15 kgm²
- 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**

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**
- kdynCurrent = 5
- kdynSpeed = 1

**Speed Controller**
- kpSpeed = 29.3
- TiSpeed = 0.024s
- TauMax = 1.2 tau_nominal = 76Nm

**Simulation time**
- t = 2s

Monitoring, Energy and Drive Technologies
Exercise 1: Examples with a Chopper and a DC Machine

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

- `monitoringEnergyandDriveTechnologies33`
DCPMQS01: System Analyses

- The machine does not reach the desired acceleration close to \( w_{\text{Nominal}} \).
  - **Display from dcpmq.controlBus:** \( v_{\text{Machine}}, v_{\text{MachineMax}}, v_{\text{DC}}, i_{\text{Machine}}, i_{\text{MachineMax}}, w_{\text{Mechanical}}, w_{\text{Ref}}, \tau_{\text{Ref}} \)
  - **Display furthermore:** \( \text{speedController.TauMax} \)
  - The torque limit \( \tau_{\text{Max}} \) is too low.
  - Increase \( \tau_{\text{Max}} \)

Exercise 1: Examples with a Chopper and a DC Machine

**AC Circuits**

Chapter 3
Chapter 3: AC Circuits

AC Signal Values

- Peak value
  \[ v_{\text{peak}} = V \]

- RMS value
  \[ V_{\text{RMS}} = \sqrt{\frac{1}{T} \int_0^T v^2(t) \, dt} \]

- Rectified mean value
  \[ |V| = \frac{1}{T} \int_0^T |v(t)| \, dt \]

- Mean value
  \[ V = 0 \]

- Rectified mean value
  \[ |V| = \sqrt{\frac{1}{T} \int_0^T v^2(t) \, dt} \]

- Peak value
  \[ v(t)|_{t=\frac{T}{2}} = V = \hat{V} \cdot \sin(\omega t) \]

Three Phase Star Connection

- \( v_{12} \) 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:

- \( V_{\text{line to line}} = \sqrt{3} \cdot V_{\text{phase}} \)
- \( I_{\text{lead}} = I_{\text{phase}} \)
Three Phase Delta Connection

\[ V_{12} \text{ line to line} = V_1 \text{ phase} \]
\[ V_{23} \text{ line to line} = V_2 \text{ phase} \]
\[ V_{31} \text{ line to line} = V_3 \text{ phase} \]

\[ i_1 \text{ load} = i_1 \text{ phase} - i_3 \text{ phase} \]
\[ i_2 \text{ load} = i_2 \text{ phase} - i_1 \text{ phase} \]
\[ i_3 \text{ load} = i_3 \text{ phase} - i_2 \text{ phase} \]

RMS values - symmetrical conditions:
\[ I_{\text{lead}} = \sqrt{3} \cdot I_{\text{phase}} \]
\[ V_{\text{line to line}} = V_{\text{phase}} \]

Name Plate Excerpts

Name plate design 1:
- \( p = 2 \)
- \( f_{\text{nominal}} = 130 \) Hz
- \( V_n = 9.11 \) Y
- \( I_{\text{nominal}} = 12.7 \) A

Name plate design 2:
- \( p = 2 \)
- \( f_{\text{nominal}} = 130 \) Hz
- \( V_n = 5.26 \) V
- \( I_{\text{nominal}} = 22 \) A

Name plate design 3:
- \( p = 2 \)
- \( f_{\text{nominal}} = 130 \) Hz
- \( V_n = 9.11/5.26 \) V/Y/\( \Delta \)
- \( I_{\text{nominal}} = 12.7/22 \) A/Y/\( \Delta \)
Principle Assembly

- Stator winding
  - Three phases
  - Symmetrical
- Pole wheel
  - Permanent magnets
  - Approximately sinusoidal field distribution
Chapter 4: Permanent Magnet Synchronous Induction Machines

Equivalent Circuit

- Magnetically symmetric
- Synchronous d-reactance
  \[ X_d = X_{dfm} + X_d \]
- Stator stray reactance
  \[ X_d \]
- Load angle
  \[ \theta \]

\[ V_s = R_s I_s + j X_d I_s + V_p \]
\[ V_p = j \Omega \psi_{PM} \]

- Field Oriented Control (FOC)
  \[ I_{s,q} \psi_{PM} \Rightarrow T_{electric} \]
  \[ I_{s,d} \psi_{PM} \Rightarrow \text{Field Weakening} \]

Parameter List of the PMSM Model
Finding the nominal shaft speed

- Example 1: PMSM \( n_{\text{Nominal}} = 1500\text{rpm}, \ p = 2 \)

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

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

- Example 2: PMSM \( f_{\text{Nominal}} = 120\text{Hz}, \ p = 4 \)

\[
\omega_{cl,\text{Nominal}} = f_{\text{Nominal}} \cdot \frac{2\pi}{2\pi} = 754 \frac{\text{rad}}{s}
\]

\[
\Omega_{m,\text{Nominal}} = \frac{\omega_{cl,\text{Nominal}}}{p} = 188 \frac{\text{rad}}{s} \Rightarrow n_{\text{Nominal}} = 1800\text{rpm}
\]

Converter Fed Three Phase Machine

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

![Diagram of DC-link voltage limits]
Example with a PM Synchronous Machine

Exercise 2

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
Exercise 2: Examples with a Permanent Magnet Synchronous Machine

SMPMQS01: Component Paths

- SmartElectricDrives.Converters.IdealSwitching.ACDC.ThreePhaseDiodeBridge
- SmartElectricDrives.Converters.AuxiliaryComponents.BufferingCapacitor
- SmartElectricDrives.QuasiStationaryDrives.SMPMSupplyDC
- Modelica.Blocks.Sources.TimeTable
- SmartElectricDrives.Interfaces.BusAdaptors.TauRefIn

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**
  - \( m = 3 \)
  - \( V = 110\text{V} \)
  - \( \text{freqHz} = 50\text{Hz} \)
  - \( R = 1e-5\Omega \)
  - \( L = 1e-4\text{H} \)

- **Diode bridge**
  - \( \text{IC} = 400\text{A} \)
  - \( f = 50\text{Hz} \)

- **Buffer**
  - \( C = 0.07\text{F} \)
  - \( R = 1e5\Omega \)
  - \( V_{0} = 3\sqrt{3} 110\text{V} / \pi \)

- **TimeTable**
  - \( \text{table} = [0,0; 0.1,0; 0.3,\tau_{\text{Nominal}}/4; 0.5,\tau_{\text{Nominal}}/4; 0.6,\tau_{\text{Nominal}}; 0.8,\tau_{\text{Nominal}}] \)

- **QuadraticSpeedDependentTorque**
  - \( \tau_{\text{Nominal}} = -214\text{Nm} \)
  - \( \omega_{\text{Nominal}} = 157\text{rad}^{-1} \)

- **Inertia**
  - \( J = 0.01\text{kgm}^{2} \)
  - \( t = 2\text{s} \)

**SMPMQS01: System Analyses**

- The electric torque of the machine follows the desired torque with satisfactory precision.
  - **Display from smpmq.s.controlBus:** \( v_{\text{Machine}}, v_{\text{MachineMax}}, v_{\text{DC}}, i_{\text{Machine}}, i_{\text{MachineMax}}, w_{\text{Mechanical}}, \tau_{\text{Ref}} \)
  - **Display furthermore:** \( \tau_{\text{Electrical}}, \text{smpmq.isd}, \text{smpmq.isq} \)
The SmartElectricDrives library
A powerful tool for electric drive simulation

Thanks for your time

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