Simulation of Power Electronic Systems with

Christian Schaffner, Plexim GmbH
Contents

- Company Plexim
- Simulation of power electronic systems
  - Challenges
  - System vs. circuit simulation
- Advantages of software PLECS
  - State-space equations
  - Ideal switches
- Control of simulation step size
  - Variable vs. fixed time steps
- Simulation of parasitic effects
  - Diode reverse recovery
- Live Demos
Who We Are

- **Start-up in Switzerland**
  - Swiss Federal Institute of Technology (ETH), Zurich
  - Plexim founded in 2002
  - Customers in more than 25 countries
  - 5 employees
  - Profitable from beginning

- **PLECS**
  - Toolbox for Simulink
  - Simulation of power electronics and electrical drives
Development of power electronic systems today

Use of traditional simulation programs:
- Complicate to operate
- Convergence problems
- Long computation time
- Expensive (TCO)

Implications:
- Need for specialized personnel
- Products not optimized
- Long time-to-market
- Expensive end products
## System vs. Circuit Simulation

### Requirement: Accurate and efficient simulation of electrical circuit and control system

<table>
<thead>
<tr>
<th>System simulators</th>
<th>Circuit simulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MATLAB/Simulink)</td>
<td>(Simplorer, PSpice, Saber)</td>
</tr>
<tr>
<td>✗ Easy set-up of controllers</td>
<td>✗ Easy set-up of circuit</td>
</tr>
<tr>
<td>✗ Circuit equations must be provided</td>
<td>✗ Incorporation of controllers often difficult</td>
</tr>
<tr>
<td>✗ Switch models too detailed</td>
<td></td>
</tr>
</tbody>
</table>

⇒ PLECS
Simulink toolbox PLECS

- Simulation of power electronic systems in PLECS
  - Evaluation of new concepts
  - Virtual prototypes
  - Performance optimization

- Controls modeled in Simulink
- Post processing in MATLAB

- Technology
  - C++, Matlab (GUI)
  - FLEXlm (license management)
  - Multiple OS support
Customer Benefits

PLECS:
- Ease of use
- Inherently robust algorithm
- Fast simulation (factor 10...100 speed gain)
- Best cost-benefit ratio for most applications
- Extensibility through open model architecture

⇒ Reduced R&D costs
  Reduced time-to-market
  Reduced quality costs
Example: Direct Torque Control
Working Principle of PLECS

- Circuit transformed into state-variable system
- One set of matrices per switch combination
High Speed Simulations with Ideal Switches

Conventional continuous diode mode
- Arbitrary static and dynamic characteristic
- Snubber often required

Ideal diode model in PLECS
- Instantaneous on/off characteristic
- Optional on-resistance and forward voltage
Comparison: Diode Rectifier

- Simulation with conventional and ideal switches

Simulation steps:
1160 → 153

Computation time:
0.6s → 0.08s
Benchmarks

- Examples from SimPowerSystems
- Comparison from ETH Zurich

<table>
<thead>
<tr>
<th>System</th>
<th>PLECS</th>
<th>SimPowerSystems</th>
<th>Simpler</th>
<th>Simulation time in seconds:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductive current chopping</td>
<td>2.4</td>
<td>3.9</td>
<td>22</td>
<td></td>
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<tr>
<td>3-phase thyristor rectifier</td>
<td>2.5</td>
<td></td>
<td>16</td>
<td></td>
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<tr>
<td>Buck converter with GTO</td>
<td>3.7</td>
<td></td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Chopper-fed dc motor drive</td>
<td>4.6</td>
<td></td>
<td>16.9*</td>
<td></td>
</tr>
<tr>
<td>3-phase half-bridge rectifier</td>
<td>4.8</td>
<td></td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>PWM–VSI with diode rectifier</td>
<td>4.8</td>
<td></td>
<td>31*</td>
<td></td>
</tr>
<tr>
<td>Vector controlled ac drive</td>
<td>8.2</td>
<td></td>
<td>17*</td>
<td></td>
</tr>
</tbody>
</table>

* fixed timestep simulation
Variable Time-Step Simulation: Buck Converter

- Transistor conducts
- Diode blocks

\[ \begin{align*}
  u_D & \quad i_L \\
  i_D & \quad u_D
\end{align*} \]
Variable Time-Step Simulation: Buck Converter

- Transistor opens
- Impulsive voltage across inductor
Variable Time-Step Simulation: Buck Converter

- Impulsive voltage closes diode

\[ u_D \]

\[ i_L \]

\[ i_D \]

\[ u_D \]
Variable Time-Step Simulation: Buck Converter

- Transistor open
- Diode conducts
Variable Time-Step Simulation: Buck Converter

Switch timing Problem:
- Diode opens too late
- Impulsive voltage across inductor
Variable Time-Step Simulation: Buck Converter

Zero-Crossing Detection:
- Time-step is reduced
- Diode opens exactly at the zero-crossing

\[ \begin{align*}
\text{Diode} & \quad \text{Diode} \\
\text{Current} & \quad \text{Current} \\
\text{Voltage} & \quad \text{Voltage}
\end{align*} \]
Innovation Built into PLECS

- Combination of existing concepts:
  - Power semiconductors modeled as ideal switches
  - Circuit as explicit differential equations
  - Virtual Dirac voltages for diode control

- Innovation: Concepts above made feasible through
  - Own algorithms
  - Numerical methods

- Outlook:
  - Real-time simulation
Variable vs. Fixed Time-Step Simulation

Variable Time-Step

- Highest Accuracy
- Can get slow for large system

Fixed Time-Step

- Can speed up simulation for large systems
- Hardware controls are often implemented in fixed time-step
- Non-sampled switching events (diodes, thyristors) require special handling

Conclusion: Both simulation methods have their application
Handling of Non-Sampled Switching Events

Diode currents
- Backward interpolation
  - Diode 3 starts conducting
- Forward step
- Forward step
- Forward step

Diode voltage
- Backward interpolation
  - Sync. with sample time
- Non-sampled zero-crossing
- Backward interpolation
  - Diode 2 stops conducting
- Backward interpolation
  - Sync. with sample time
Diode turn-off in different blocking conditions

Test circuit:
Standard Diode Model Characterized by $R_{on}/V_f$

- Diode turn-off in different blocking conditions

Test circuit:

![Diode test circuit diagram]

*Graphs showing diode current and voltage over time.*
Dynamic Diode Model with Reverse Recovery

**Behavioral Model**
Dynamic Diode Model with Reverse Recovery

- Reverse recovery current and over voltage in different blocking conditions

Behavioral diode model:
<table>
<thead>
<tr>
<th></th>
<th>PLECS</th>
<th>SimPowerSystems</th>
<th>PSIM</th>
<th>Simulor</th>
<th>PSpice</th>
<th>SABER</th>
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<tbody>
<tr>
<td>Designed for power electronics</td>
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<td>✔️  ✔️</td>
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<tr>
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<tr>
<td>Fixed time-step</td>
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<td>✔️  ✔️</td>
<td>✔️  ✔️</td>
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<tr>
<td>Variable time-step</td>
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<tr>
<td>Ideal switches</td>
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<td>✔️  ✔️</td>
<td>✔️  ✔️</td>
<td>✔️  ✔️</td>
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<td>Easy to use</td>
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<tr>
<td>Fast</td>
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<tr>
<td>Cost</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$$</td>
<td>$$$</td>
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</tbody>
</table>

**Competitive offerings**
Reference Customers

Some of our customers:

- ABB
- Alstom
- Bombardier
- Bosch
- Conti TEMIC
- Hilti
- Panasonic
- Philips
- Siemens
- Smiths Aerospace
- Tyco Electronic Power S.
- Vestas Wind Systems
- RWTH Aachen
- Aalborg University
- CERN
- Chalmers University
- DLR
- TU Dresden
- Florida State University
- Ghent University
- Imperial College London
- University of Manchester
- Purdue University
- Warsaw University of Technology
Application example: Efficiency comparison

- Project at ABB
- Air-cooled MV drive system
- Measurement of losses difficult
- PLECS used for simulation of
  - Switching losses
  - Filter losses
  - Harmonics

Source: Y. Suh, J. Steinke, P. Steimer: Efficiency comparison of voltage source and current source drive systems for medium voltage applications, EPE 2005
Application example: Optimum controller design

- Project at ABB Corporate Research
- Multilevel AC-DC converter system with 16 stages
- 12 switches per stage
  \[\Rightarrow \text{192 independent switches}\]
- Simulink used for controls
- PLECS used for electrical circuit

Source: O. Aydin, A. Akdag, P. Stefanutti, N. Hugo: Optimum controller design for a multilevel AC-DC converter system, APEC 2005
Continuous research

- Behavioral device models (Q2 2006)
  - Diode with reverse recovery
- Thermal simulation (Q3 2006)
  - Switching losses
- Real-time simulation (Q1 2007)
  - Project with ETH Zurich funded by Swiss government
- Magnetic circuit simulation (Q3 2007)
  - Saturation, hysteresis
Thank you

For more information about PLECS, please contact us at

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