Model-Based E-Drive Dimensioning

Dr. Florian Loos, Navid Daniali, Dr. Markus Schäfer | E-Mobility
Agenda

1. E-Mobility @ ZF
2. E-Drive Concept
3. Matlab Inverter Model
4. Applications
5. Conclusion & Outlook
01

E-Mobility @ ZF
ZF Technology Domains

- Vehicle Motion Control
- Automated Driving
- Electric Mobility
- Integrated Safety

Digitalization / Internet of Things
ZF electrifies everything on wheels
From bikes and cars to trucks and buses
Roadmap Electric Vehicle Drive

Power

Today

Future topics

Scalable platform:
• 80KW to >200KW
• Axial parallel architecture
• Low cost solutions

Additional functions:
• 2 speed
• Disconnect
• 800V
• Parking lock next Gen.

Next Generation Market Entry

2019 2020 2021 2022 2023 2024
02 E-Drive Concept
Components of an E-Drive System
Components of an E-Drive System

Energy source

Electrical machine
Components of an E-Drive System

- Energy source
- Power Inverter
- Electrical machine
# Power Inverter vs. Electric Cettle

<table>
<thead>
<tr>
<th></th>
<th>Power Inverter</th>
<th>Electric Cettle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume</strong></td>
<td>4.1 dm³</td>
<td>3.0 dm³</td>
</tr>
<tr>
<td><strong>Power Output</strong></td>
<td>150 kW</td>
<td>2.2 kW</td>
</tr>
<tr>
<td><strong>Max. Power Loss</strong></td>
<td>5 kW</td>
<td>0</td>
</tr>
<tr>
<td><strong>(Heating) Power / Area</strong></td>
<td>139 W/cm²</td>
<td>19 W/cm²</td>
</tr>
</tbody>
</table>
Power Inverter in action - „139W/cm²“
Components of an E-Drive System

**Energy source**

**Power Inverter**

**Electrical machine**

**CHALLENGE:** Development of an E-Drive system that is
- efficient,
- highly performant and
- very resistant to damages.
Fields of Application of Matlab/Simulink @ ZF E-Drive Systems

- Efficiency calculations
- Capacitor dimensioning
- Semiconductor module dimensioning
- Cooling concept
- Lifetime considerations

Component Dimensioning and Hardware Development

- Derating strategy
- Modulation methods
- Controller design

Functions and Software Development

- Measurement evaluations (e.g. Double Pulse, Zth, Power Hill)
- Parameter identification for simulations
- Evaluation of generated data

Validation and Verification

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Matlab Inverter Model
Matlab Inverter Model

- Efficiency Diagrams
- Performance Diagrams
- Lifetime Calculations
- Derating Strategy

- Operating Data
- Thermal Parameters
- Lifetime Model
- System Parameters
- ...
Structure Inverter Model

Inverter Model

Thermal Model

Coolant
- IGBTs Highside
- Diodes Highside
- IGBTs Lowside
- Diodes Lowside

Loss Model

Standard Operation Mode

Highside
- IGBTs
- Diodes
- Switching Losses
- Conduction Losses

Lowside
- IGBTs
- Diodes
- Switching Losses
- Conduction Losses

Active Short Circuit

Highside
- IGBTs
- Diodes
- Switching Losses
- Conduction Losses

Lowside
- IGBTs
- Diodes
- Switching Losses
- Conduction Losses

Lines of Matlab Code

~10,000

Σ Simulink Blocks

>>3,000

ca. 10 years of development
Efficiency and Performance Calculations
CO₂ reduction: Every gram counts

Conventional drivelines

Hybrid drivelines

Electric drivelines
Example of Loss and Efficiency Calculation

Losses

Efficiency

Power Electronics

Electrical Machine

E-Drive System
Example of Loss and Efficiency Calculation

Losses

Efficiency

Power Electronics

Electrical Machine

E-Drive System

→ Losses and efficiency of entire E-Drive system calculated over torque and speed range
Matching of E-Machine and Power Inverter

→ Left inverter undersized, right one appropriate for electrical machine
Life€-€€e Prediction
Different extension coefficients result in thermal stress.
Each junction can absorb a certain amount of energy and will fail afterwards.

\[ P_{\text{Loss}} = f(I_{\text{ac}}, f_{\text{sw}}, U_{\text{dc}}, T_{\text{KM}}, ..) \]

To predict time to failure of each junction, thermal stress has to be described mathematically.

Image source:
G. Farks, D. Schweitzer, Z. Sarkany, M. Rencz
On the Reproducibility of Thermal Measurements and of Related Thermal Metrics in Static and Transient Tests of Power Devices
Workflow Lifetime Prediction

- "Mission Profile" of Electr. Drive (M, v, U_Batt)
- Simulate Model EM
- "Mission Profile" of Power Electronics (U_{DCr}, I, \cos \phi, m, f_m)
- Simulate Model PE
- Temperature Profile Semiconductor (T_{IGBT}, T_{Diode})
- Rainflow Classification
- Load Cycle of Semiconductor (∆T-Histogram)

Temperature Profile

- Semiconductor (T_{IGBT}, T_{Diode})
- Rainflow Classification
- Load Cycle of Semiconductor (∆T-Histogram)

Life Cycle Consumption of Semiconductors

- Palmgren Miner
- Lifetime Consumption of Semiconductors
- Weibull Distribution
- Probability of Failure of Semiconductors

Coolant Temperature + Coolant Flow Rate

Input of Power Cycling Test Results

- Power Cycling Stability
- Lifetime Consumption per Temperature Rise
### Example of Lifetime Prediction

#### Cooling temperature in °C

<table>
<thead>
<tr>
<th>Drive Cycle 1</th>
<th>Drive Cycle 2</th>
<th>Drive Cycle 3</th>
<th>Drive Cycle 4</th>
<th>Drive Cycle 5</th>
<th>Drive Cycle 6</th>
<th>Drive Cycle 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>1.255%</td>
<td>1.051%</td>
<td>0.716%</td>
<td>1.043%</td>
<td>0.765%</td>
<td>0.819%</td>
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<td>-30</td>
<td>2.409%</td>
<td>2.013%</td>
<td>1.365%</td>
<td>1.994%</td>
<td>1.461%</td>
<td>1.563%</td>
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<tr>
<td>-20</td>
<td>4.481%</td>
<td>3.734%</td>
<td>2.522%</td>
<td>3.691%</td>
<td>2.703%</td>
<td>2.891%</td>
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<tr>
<td>-15</td>
<td>6.046%</td>
<td>5.032%</td>
<td>3.391%</td>
<td>4.967%</td>
<td>3.636%</td>
<td>3.888%</td>
</tr>
<tr>
<td>-10</td>
<td>8.104%</td>
<td>6.734%</td>
<td>4.528%</td>
<td>6.640%</td>
<td>4.858%</td>
<td>5.195%</td>
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<tr>
<td>-5</td>
<td>10.021%</td>
<td>8.382%</td>
<td>5.658%</td>
<td>8.268%</td>
<td>6.060%</td>
<td>6.475%</td>
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<tr>
<td>0</td>
<td>12.313%</td>
<td>10.373%</td>
<td>7.031%</td>
<td>10.237%</td>
<td>7.518%</td>
<td>8.023%</td>
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<tr>
<td>5</td>
<td>13.961%</td>
<td>11.960%</td>
<td>9.753%</td>
<td>11.835%</td>
<td>8.734%</td>
<td>9.294%</td>
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<tr>
<td>10</td>
<td>16.357%</td>
<td>14.125%</td>
<td>11.539%</td>
<td>13.999%</td>
<td>10.358%</td>
<td>11.001%</td>
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<tr>
<td>15</td>
<td>19.063%</td>
<td>16.591%</td>
<td>13.770%</td>
<td>16.474%</td>
<td>12.223%</td>
<td>12.954%</td>
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<tr>
<td>20</td>
<td>22.560%</td>
<td>19.713%</td>
<td>14.322%</td>
<td>19.598%</td>
<td>14.563%</td>
<td>15.412%</td>
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<tr>
<td>25</td>
<td>26.583%</td>
<td>23.320%</td>
<td>14.544%</td>
<td>23.216%</td>
<td>17.278%</td>
<td>15.674%</td>
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<tr>
<td>30</td>
<td>22.326%</td>
<td>19.845%</td>
<td>15.034%</td>
<td>19.935%</td>
<td>14.925%</td>
<td>15.888%</td>
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<tr>
<td>35</td>
<td>22.372%</td>
<td>20.034%</td>
<td>18.883%</td>
<td>20.229%</td>
<td>15.185%</td>
<td>16.360%</td>
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<tr>
<td>40</td>
<td>22.964%</td>
<td>20.600%</td>
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<td>20.848%</td>
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<td>20.556%</td>
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<tr>
<td>45</td>
<td>28.918%</td>
<td>25.923%</td>
<td>36.504%</td>
<td>26.205%</td>
<td>19.667%</td>
<td>25.720%</td>
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<tr>
<td>50</td>
<td>36.264%</td>
<td>32.485%</td>
<td>45.124%</td>
<td>32.800%</td>
<td>24.607%</td>
<td>32.051%</td>
</tr>
<tr>
<td>55</td>
<td>45.296%</td>
<td>40.546%</td>
<td>55.78%</td>
<td>40.889%</td>
<td>30.662%</td>
<td>39.786%</td>
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<tr>
<td>60</td>
<td>56.361%</td>
<td>50.412%</td>
<td>62.444%</td>
<td>50.776%</td>
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<td>49.201%</td>
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<tr>
<td>65</td>
<td>69.869%</td>
<td>62.444%</td>
<td>77.073%</td>
<td>62.818%</td>
<td>47.065%</td>
<td>60.626%</td>
</tr>
<tr>
<td>70</td>
<td>86.308%</td>
<td>77.073%</td>
<td>62.818%</td>
<td>77.437%</td>
<td>57.991%</td>
<td>60.626%</td>
</tr>
</tbody>
</table>

#### Distr. Cold

<table>
<thead>
<tr>
<th>Drive Cycle 1</th>
<th>Drive Cycle 2</th>
<th>Drive Cycle 3</th>
<th>Drive Cycle 4</th>
<th>Drive Cycle 5</th>
<th>Drive Cycle 6</th>
<th>Drive Cycle 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,10%</td>
<td>0,20%</td>
<td>0,30%</td>
<td>0,70%</td>
<td>2,00%</td>
<td>3,00%</td>
<td>2,00%</td>
</tr>
<tr>
<td>0,00%</td>
<td>0,00%</td>
<td>0,00%</td>
<td>0,00%</td>
<td>2,00%</td>
<td>3,00%</td>
<td>2,00%</td>
</tr>
</tbody>
</table>

#### Distr. Hot

<table>
<thead>
<tr>
<th>Drive Cycle 1</th>
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<th>Drive Cycle 3</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0,00%</td>
<td>0,00%</td>
<td>0,00%</td>
<td>0,00%</td>
<td>2,00%</td>
<td>3,00%</td>
<td>2,00%</td>
</tr>
</tbody>
</table>

#### Lifetime consumption

![Diagram showing lifetime consumption variation with cooling temperature for different drive cycles.](image-url)
05

Conclusion & Outlook
Conclusion & Outlook

Conclusion

• Challenge: E-Drive system → efficient, highly performant and persistent
• Development of Matlab/Simulink environment:
  enables evaluation of efficiency, performance, lifetime
• Entire E-drive system can be correctly dimensioned, improved and optimized by simulation!

Outlook

• Increase of level of automation
• Combining Matlab/Simulink environment with CAD-, FEM- and CFD-simulation environments
• Integration of EMC simulation in our simulation environment
Questions & Answers

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