Die FEM-Simulation als integraler Bestandteil
während der Musterphase in der Motorenberechnung

Philipp Siehr
• 2009 – 2016  **Mathematics** (Ruprecht-Karls University Heidelberg)

• 2016 – 2018:  **Simulation Engineer** (AMK Automotive GmbH & Co.KG)
  • Electric Drives for industry and automotive
  • Development of a tool using Ansys Maxwell to simulate a set of >10000 motor designs. It is possible to find configurations for specific customer requests within seconds.

• Since 2018:  **Business Development Manager** (CADFEM GmbH)
  • Focus on computation of electric drives:
    • Early design phase
    • Detailed analysis in all physical domains
    • System level integration
CADFEM – Simulation is more than Software

PRODUCTS
Software und IT Solutions

SERVICES
Advice, Support, Engineering

KNOW-HOW
Transfer of knowledge

CADFEM in D, A, CH
• 1985 founded
• 2,300 customers
• 10 locations
• 220 employees (worldwide > 350)
• ANSYS Elite Channel Partner
Big Industry Trends

Internet of Things

2018: 11bn connected things
2020: 20bn connected things
Quelle: Statista.com

5G

2013: „Neuland“
2018: „Noch nicht durchschrittenes Terrain“
Angela Merkel

Electrification

Next slide
Anteil von Elektro- und Hybridautos in Norwegen steigt auf 53 Prozent

11.07.2017
Diesel und Benziner erstmals in der Minderheit

From the Idea to the Operation

Design ⟷ Analysis ⟷ Operation

Design
Efficient Motor Design Toolkit

2D & 3D Analysis
Advanced Magnetics Modelling

Coupled Analysis
NVH, Cooling, ...

System Validation
Control logic, software

Motor-CAD
Thermal Emag

Maxwell 2D & 3D

Mechanical & CFD

3D Physical Validation

Twin Builder

© CADFEM 2019 Praxisforum Elektrische Antriebstechnik (P. Siehr)
Objectives

• Investigation of the possibilities
• **Fast** evaluation of different designs
• Coupled preliminary electromagnetic and thermal analysis
• **Fast** evaluation of performance maps and duty cycles

Requirements

• Software to evaluate fast and accurate electromagnetic and thermal behaviour
• Automated workflows for data exchange
• Capability for preliminary optimization and sensitivity analysis
Motor-CAD Software

- Motor-CAD modules are developed to enable fast and accurate analysis in one integrated software
  
  - **EMag** - Combined 2D FEA and analytical algorithms for fast calculation of electromagnetic performance.
  
  - **Therm** - Heat transfer and flow network circuits automatically set up to provide steady-state and transient thermal predictions.
  
  - **Lab** - Efficiency mapping and drive cycle analysis within minutes.
  
  - **Mech** - 2D FEA based solution in Motor-CAD to analyse stress and displacement in rotors during operation.

- Written by motor design experts in the language of the motor designers so very easy to use.
### Example Specification Sheet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC supply voltage</td>
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<td></td>
</tr>
<tr>
<td>Peak torque</td>
<td>300 Nm</td>
<td></td>
</tr>
<tr>
<td>Base speed</td>
<td>6000 rpm</td>
<td></td>
</tr>
<tr>
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</tr>
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<tr>
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<td>Liquid</td>
<td></td>
</tr>
<tr>
<td>Volume (L/W/H)</td>
<td>115 / 270 / 270 mm</td>
<td></td>
</tr>
</tbody>
</table>
Geek vs. Nerd

Geek
- Highly Theoretical
- Pen&Paper-Solution
- Analytical Formulas

Nerd
- Pure FEM
- HPC-Cluster
- Parameter studies
- Optimization

• Theory based idea
• Verify with FEM
• Optimize
### Design Phase – Motor Type

<table>
<thead>
<tr>
<th></th>
<th>IM</th>
<th>BPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density Torque</td>
<td>+/-</td>
<td>++</td>
</tr>
<tr>
<td>Efficiency</td>
<td>+/-</td>
<td>++</td>
</tr>
<tr>
<td>Weight</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Inverter</td>
<td>+</td>
<td>+/-</td>
</tr>
<tr>
<td>Cost Motor</td>
<td>+/-</td>
<td>-</td>
</tr>
<tr>
<td>Cost System</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>Sound</td>
<td>+</td>
<td>++</td>
</tr>
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</table>

- Brushless Permanent Magnet Motors are most common as traction motors
- Tesla is one of the few companies using Induction Motors. Tesla Model 3 uses „AC induction front & switched reluctance, partial permanent magnet rear.“ (Twitter, @elonmusk, 19. Mai 2018)
- The 2018 Audi e-tron also uses an IM Motor

Quelle: Seminar Prof. Dr. phil. Dr.-Ing. habil. Harald Neudorfer
### Parameter | Value | Unit
--- | --- | ---
DC supply voltage | 450 V |  
Max AC line current | 900 A (peak) |  
Peak output power | 235 kW |  
Peak torque | 300 Nm |  
Base speed | 6000 rpm |  
Max speed | 15000 rpm |  
Continuous power at base speed | 80 kW |  
Continuous torque at base speed | 100 Nm |  
Cooling System | Liquid |  
Volume (L/W/H) | 115 / 270 / 270 mm |  

- For a rotational movement the electromagnetic torque is given by:
  \[ T = \frac{\pi^2}{4\sqrt{2}} \cdot k_{w1} ABD^2 L_{fe} \]
  - \( k_{w1} \): fundamental winding factor
  - \( L_{fe} \): the axial active length
  - \( A = \frac{\text{Total Amp–Cond.}}{\text{Airgap–circ.}} = \frac{2mN_{ph}I_{RMS}}{\pi D} \), electric loading
  - \( B = \frac{\text{avg. flux dens}}{\text{surface}} = \frac{2p\phi}{\pi DL_{fe}} \), magnetic loading
Design Phase – Estimate Dimension

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- For a rotational movement the electromagnetic torque is given by:
  \[
  T = \frac{\pi^2}{4\sqrt{2}} \cdot k_{w_1} \cdot A \cdot B \cdot D^2 \cdot L_{fe}
  \]
  - \( k_{w_1} \) fundamental winding factor
  - \( L_{fe} \) the axial active length

- \( A = \frac{\text{Total Amp–Cond.}}{\text{Airgap–circ.}} = \frac{2mN_{ph}I_{RMS}}{\pi D} \), electric loading

- \( B = \frac{\text{avg. flux dens}}{\text{surface}} = \frac{2p\phi}{\pi D L_{fe}} \), magnetic loading

- With \( V_{rotor} = \frac{\pi}{4} D^2 L_{fe} \) it follows:
  \[
  TRV := \frac{T}{V_{rotor}} = \frac{\pi}{\sqrt{2}} k_{w_1} A B \]
Design Phase – Estimate Dimension

\[ TRV = \frac{T}{V_{\text{rotor}}} = \frac{\pi}{\sqrt{2}} k_{w1} AB \]

- Values from experience or literature

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>TRV [kN/m³]</th>
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<tbody>
<tr>
<td>Enclosed Motor - ferrite</td>
<td>5-15</td>
</tr>
<tr>
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- Small remark: Since A~I and B~ϕ we can directly see T~Iϕ.
Design Phase – Estimate Dimension

\[ TRV = \frac{T}{V_{rotor}} = \frac{\pi}{\sqrt{2}} k_{w1} AB \]

We assume:
- stator/rotor ratio: 0.55
- Active length: max. 0.8*L
- Active Diameter: 10mm for cooling

- \( TRV_{peak} = \frac{300 \times 2^2}{\pi(0.55 \times 0.26)^2 \times 0.115 \times 0.8} \times 0.001 = 203 \text{ kN/m}^3 \)
- \( TRV_{cont} = \frac{100 \times 2^2}{\pi(0.55 \times 0.26)^2 \times 0.115 \times 0.8} \times 0.001 = 68 \text{ kN/m}^3 \)

⇒ Rare-Earth, liquid cooled.
⇒ Rotor diam 145mm, Stator diam 260mm, \( L_{Fe} = 90\text{mm} \)

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The fundamental frequency is given by

\[ f = \frac{np}{60} \]

with \( n \) in rpm, \( p \) pole pairs.

<table>
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<tr>
<th>Pole pairs (p)</th>
<th>Fundamental frequency (f) [Hz]</th>
</tr>
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<tr>
<td>1</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>750</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>1250</td>
</tr>
<tr>
<td>6</td>
<td>1500</td>
</tr>
</tbody>
</table>

Inverter has to be able to modulate.
Design Phase – Number of Poles

- **Advantages of higher pole number:**
  - Higher TRV, due to reduced leakage
  - Lower dimension of stator back iron
  - Reduced end-winding dimensions → reduced copper loss

- **Disadvantages of higher pole number:**
  - Higher inverter losses
  - Higher magnet losses
  - Requires short pole pitch → concentrated windings.
  - Lower reluctance torque

**Manufacturability**

⇒ Let’s choose 4 pole pairs (p=4).

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</table>
• The possible number of slots \([s]\) can be chosen with respect to:
  
  - \(s > p\)
  
  - \(\frac{s}{m \cdot parallel\_paths} \in \mathbb{N}, m = phases\)
  
  - \(\frac{p}{parallel\_paths} = 2k, k \in \mathbb{N}\)
  
  - \(\frac{s}{m \cdot \text{gcd}(s,p)} \in \mathbb{N}\)

• With \(p=4\), we can choose:
  
  \(s \in \{12,24,36,48,72,84 \ldots \}\)

\(\Rightarrow\) We choose \(s=48\), based on the circumference at the airgap (~450mm), and cooling properties.

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Design Phase – Rotor

- Surface Mounted
- Interior / Tangential
- V-Shape
- U-Shape
- Spoke / Radial
Design Phase – Initial Design

### Table: Design Parameters

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<tr>
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<tr>
<td>Rotor Diam</td>
<td>145</td>
<td>mm</td>
</tr>
<tr>
<td>Stator Diam</td>
<td>260</td>
<td>mm</td>
</tr>
<tr>
<td>$L_{Fe}$</td>
<td>216</td>
<td>mm</td>
</tr>
<tr>
<td>Pole pairs</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Slots</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Rotor Topology</td>
<td>V-shape, 2layer</td>
<td></td>
</tr>
</tbody>
</table>

Choice of Magnet Volume: Based on FEA computation I=0A and airgap flux density of B=0.7-0.9T.

B=0.78T
### Design Phase – Initial Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phases</td>
<td>3</td>
</tr>
<tr>
<td>Connection Type</td>
<td>Star</td>
</tr>
<tr>
<td>Winding Pitch</td>
<td>5</td>
</tr>
<tr>
<td>Copper Slot Fill</td>
<td>0.4</td>
</tr>
<tr>
<td>Conductors/Strands(^1)</td>
<td>5*10=50</td>
</tr>
<tr>
<td>Winding Diameter (insulation/copper)</td>
<td>1.35mm / 1.25mm</td>
</tr>
</tbody>
</table>

\(^1\)Reason: manufacturability
Goal was 300Nm → Not too bad.

Possible solution:
- Axial length
- Steeper V-shape
- More Magnet Volume (1 Layer, thicker)
- Ratio diameter Stator / Rotor
Design Phase – ECE Model

- **Step 1: Model Order Reduction**  
  → ECE-model (equiv. circuit extraction)
  - Lookup-table for Torque, Flux Linkage, Voltage …
    \[ T = T(id,iq) \]
  - Includes saturation (nonlinear)
  - Does not include transient effects, e.g. eddy current loss.

- **Step 2: Control Strategy**  
  → Maximum Torque per Ampere (MTPA)

\[
\begin{align*}
\min I_s &= \sqrt{i_d^2 + i_q^2}, \\
T_{shaft} - T_{demand} &= 0 \\
\sqrt{u_d^2 + u_q^2} &\leq V_{lim}
\end{align*}
\]
Design Phase – Torque Curve

![Torque Curve Graph](image)

- $T$  Torque (Nm)
- $U_p$  Voltage (V)
- $I_p$  Current (A)

$n$ [rpm]
Design Phase – Efficiency Map
• US06 Cycle
  • 6 minutes with 600 Time/Speed Points
  • Torque due to load
• Full FEA ~1 day computation time
• ECE-Model → 10sec
Design Phase – Efficiency Map and Cycle
• Heat transfer modelled by resistance:
  \[ R_{th} = \frac{L}{kA} \]
  - **Conduction**
    - A: path area
    - L: length from geometry
    - k: thermal conductivity of material
  - **Convection**
    - h: heat transfer coefficient.
      [Test data or CFD analysis]
  - **Radiation**
    - \( \varepsilon \): emissivity, F view factor
  - **Thermal capacity**
    \[ C = c_m m \]
  - **Flow models**
Design Phase – Example

• What is the optimal amount of fins, to minimize the average temperature of the winding?

• For this example: $P_{Cu} = 500\,W$, fixed width

• Lumped Circuit: <2s for each design $\rightarrow$ <1min computation time
Design Phase – Example transient

• What is the optimal amount of fins, to minimize the average temperature of the winding – after 3 cycles US06?
  • 3 cycle = 30 min real time

• Lumped Circuit: ~75s for each design → <20min computation time
Objectives

- 3D Electromagnetic Effects
- Coupled Analysis:
  - Thermal
  - Structural
  - CFD
  - Power Electronics and System
  - Acoustics / NVH
- Generate deeper physical understanding

Requirements

- Very versatile and high-end simulation tools
- Easy coupling of all physical domains
- Sensitivity and robustness analysis over different tools and many parameters
- Workflow automation and file data handling
CADFEM ANSYS Extension - Electric Drive Acoustics inside ANSYS

Electro-magnetic Analysis → Excitation Loads (FFT) → Harmonic Vibration Analysis → Oscillation, ERP, Waterfall Plot

ANSYS GUI Enhancement
System

Design
Efficient Motor Design Toolkit

2D & 3D Analysis
Advanced Magnetics Modelling

Coupled Analysis
NVH, Cooling, ...

System Validation
Control logic, software

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Motor Design Limited

Lab

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Emag

Maxwell 2D & 3D

Mechanical &CFD

Twin Builder

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Objectives

- Analysis and optimization of a system without extensive coupled FEM simulation
- Implementation of third party behavior models
- Fast evaluation of performance maps and duty circles on a system level

Requirements

- Behavior Models generated by previously used tools
- Platform / System simulator
System Model

- Model Order Reduction → ECE-model (equiv. circuit extraction)
  - Lookup-table for Torque, Flux Linkage, Voltage …
    \[ T = T(\text{id},\text{iq}) \]
  - Includes saturation (nonlinear)
  - Does not include transient effects, e.g. eddy current loss.

- Combination of ECE Motormodel with:
  - Inverter
  - Load, Car Model
  - Thermal Behavior Model
  - Acoustic Model

- Standardized Interface: FMI / FMU
Several ideas on simulation based motor design have been presented.

First we derived an initial design based on analytical formulas, then electromagnetic FEM computations improved the model.

Thermal behavior can be simulated very fast using a lumped circuit simulation.

With the ECE Model and the lumped circuit model efficiency maps and duty cycles can be computed very quickly.

- Additional strategies are based on optimizers including:
  - Efficiency Map
  - Electromagnetic Duty Cycle
  - Continuous Torque Map
  - Thermal Duty Cycle
  - Cogging Torque
  - Torque Ripple
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