IRON LOSS CALCULATION OF AN INTERNAL PERMANENT MAGNET SYNCHRONOUS MACHINE FOR A FUEL CELL CAR

Electric Drive System Research Activities at Bern University of Applied Sciences Engineering and Information Technology

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About the Speaker

Dr. Andrea Vezzini

- Professor for Industrial Electronics since 1996 at Bern University of Applied Sciences (BFH TI) Biel
- Co-founder and Chairman of the Board of drivetek ag since 2002
- 2003 Visiting Guest Professor at General Motors Advanced Technology Center in Torrance (7 Months)
- 2007 Distinguished Visiting Scientist at Commonwealth Science and Industrial Research Organisation (CSIRO), Australia (5 Months)
- Together with drivetek ag currently involved in projects with Bombardier Transportation AG, General Motors and Porsche Motorsport
BFH Engineering and Information Technology

- Established in 1890
- Since 1998 Part of Bern University of Applied Sciences
- 6 Divisions with a total of 1’300 students, second biggest in Switzerland
- External Turnover with aR&D 2008: approx. 8 Mio. CHF (+ 2.5 Mio. CHF internal funding)
- Strategic Programs in Fuel Cell Development, Automotive Systems and Renewable Energy
- Over 10 Innovation prices since 1993
spin-off Success

drivetek ag was founded in 2002 as a fully independent spin-off of the Laboratory of Industrial Electronics. Eleven Engineers work on high efficient drives and power electronics for energy, automotive, space and automation applications. It’s the creation of jobs and industrial impulses which has become one of the most challenging but also exciting tasks of the Berne University of Applied Sciences.

http://www.drivetek.ch
Content

- Internal Permanent Magnet Synchronous Motor Fundamentals
- Design Flow
- Core Loss Calculations
- Examples

“The outcome of any serious research can only be to make two questions grow where only one grew before.”

Thorstein Veblen
US economist & social philosopher (1857 - 1929)
Types of PM Synchronous Motors

- The amount of PM-generated magnetic flux linked by the coils of the stator remains fixed.
- As a result, the back-electromotive force (back-emf) voltage induced by the PMs increases linearly with the speed of the rotor.
- As the rotor speed increases the back-emf voltage rises, which results in a rapid reduction in the available voltage, (the difference between the supply voltage and the back-emf). When there is no longer any voltage available to drive current into the stator, the maximum speed has been reached.
- Depending on the rotor geometry, PM Synchronous show different torque-speed behavior.
**Saliency**

- Saliency: different d- and q-axis inductance, based of different rotor permeability in q- and d-axis
- Salient pole machine allow for an extended constant power speed range (CPSR), required in a multitude of application.
- Combined with weak flux bonded PM (PM-Assisted SRM) and laminated rotor to reduce rotor losses
**Design of PM Synchronous Machines**

- **Normalized System Equations**
  - Surface Mounted PM SM has Saliency $\xi = 1$ and maximum torque current angle $\gamma = 0$
  - Synchronous Reluctance Machine has $\Psi_m = 0$

- **IPM Design Freedom:**
  - With strong magnetic field from PM Magnets -> conventional IPM
  - With weak magnetic field from PM Magnets -> PM Assisted SRM

- **Field Weakening Operation**
  - For surface mounted PMs, where $L_q = L_d$, $I_q$ in the negative direction weakens the magnet so that the motor may be driven at higher speeds. However, there is no increase in output power, while the input power must increase to supply the additional resistance heat loss.
IPM Constant Power Speed Range / Field Weakening

\[ V_{dn} = -\omega_n \cdot \xi \cdot L_{dn} \cdot I_n \cdot \cos(\gamma) \]

\[ V_{qn} = \omega_n \cdot \Psi_{mn} - \omega_n \cdot L_{dn} \cdot I_n \cdot \sin(\gamma) \]

- The possible operating points are limited within the current circle and the voltage ellipse. The voltage ellipse will decrease its size with increasing speed.
- Maximum torque above base speed is only possible by increasing the current angle
- Depending on the placement of the infinite speed point three different design options are available: finite speed, optimum infinite speed and infinite speed type
IPM Design Possibilities

- Infinite speed IPM with $\Psi_{mn} = 0.2$, $\xi = 3.075$, $L_{dn} = 0.4$ (red continuous line)
- Optimal Design IPM with $\Psi_{mn} = 0.4$, $\xi = 3.075$, $L_{dn} = 0.4$ (blue dotted line)
- Finite speed IPM with $\Psi_{mn} = 0.6$, $\xi = 3.075$, $L_{dn} = 0.4$ (black dashed line)

- IPM magnetic flux and saliency can be matched for ideal fit of machine characteristics to car requirements
- Lower magnetic flux can be compensated with higher saliency with the added benefit of lower current per torque requirements (for the same per unit torque and CPSR)
Optimized Motor Choice

- Based on the limits from the different requirements, the possible motor specs (base speed and nominal torque) are plotted. The red line is the combined curve all the motor specs, which will fulfill all the requirements. The three crosses are exemplary motor designs.

ZH-Pendler Drive cycle: Torque and Speed vs. Power, Torque, CPSR, m=720kg
FEA Process Overview

1. **Generic Motor Model Design**
   - Adjustments on the Motor Model (definition of Geometry, Material, etc.)

2. **Simulation of the Model**
   - Analysis in Maxwell
   - If Results are ok:
     - Parametric Analysis

3. **Result Analysis with Matlab**

4. **Efficiency Map Simulation**

**Verification**

- Verification
- Verification

1. **Design of a lumped parameter Model**
2. **Model Definition**
3. **Analysis in Maxwell**
4. **Parametric Analysis in Maxwell**
5. **Result Analysis in Matlab**
6. **Efficiency Analysis**
Maxwell –Matlab toolchain: Analysis of FEA Result Data

- Transient Simulation of a 2d-Model over 110 different current amplitude and angle cases over one electrical period.
- Simulation data is saved after each transient run (torque, flux).

- A set of matlab functions performs the necessary operations to calculate the Results of the Motor from the FEA Results.
- The Results will then be displayed and compiled into a pdf Report.
Search optimal Current and Current Angle

- Calculation of Continuous and Peak Requirement Current and Current Angles with a maximum Torque Per Ampere Approach (minimizing the Copper Losses)
- Possible Torque Operation points are reduced with increasing speed, as voltage circle decreases. In this case the current angle has to be increased and/or the current amplitude decreased (Type II)
Why not calculated Performance Curves from one single point of operation?

The effects of saturation on $L_d$ and $L_q$ are affecting the voltage equations and as a consequence the calculation of the dq-axis diagram

$$T_n = \Psi_{mn} \cdot I_n \cdot \cos(\gamma) + \frac{1}{2} \cdot (\xi - 1) \cdot L_{dm} \cdot I_n^2 \cdot \sin(2 \cdot \gamma)$$
Efficiency Map

- Calculate Simulation Parameters for Simulation Points (Current, Current Angle, Rotation Speed, Simulation Time)
- Write Parameters as Variables into Maxwellscript file for Simulation
- Simulation over at least two electrical periods for each operation point in Maxwell
Core Loss Calculation

- Improvement of V12 by using multi-frequency data. Eliminates need to change data at each simulation step.
- Maxwell uses dB/dt approach and not a fourier series Steinmetz based formula. This yields better results but requires at least two electrical periods of simulation data.

\[
p_h(t) = H_{irr} \frac{dB}{dt}, \quad H_{irr} = \frac{1}{\pi} k_h \cdot B_m \cos(\theta),
\]

\[
p_c(t) = \frac{1}{2\pi^2} k_c \left( \frac{dB}{dt} \right)^2, \quad p_e(t) = \frac{1}{C_e} k_e \cdot \left| \frac{dB}{dt} \right|^{1.5}.
\]

Measured values as dots. Calculated lines are based on Maxwell Coefficients \( K_h, K_c \), and \( K_e \) which have been calculated for each frequency accordingly.

Referenzpaper:
Problems with Core Loss Calculations using different number of triangles

27343 triangles
29591 triangles
48638 triangles

<table>
<thead>
<tr>
<th></th>
<th>27343 triangles</th>
<th>29591 triangles</th>
<th>48638 triangles</th>
</tr>
</thead>
<tbody>
<tr>
<td>torque (N-m)</td>
<td>average 56.2</td>
<td>average 56.3</td>
<td>average 56.3</td>
</tr>
<tr>
<td>coreloss (W)</td>
<td>average 1903</td>
<td>average 1791</td>
<td>average 1590</td>
</tr>
</tbody>
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The three models with different number of triangles were used to simulate the same load point using impressed currents in the phases (11k rpm, 250Arms, 77.7 DEG current angle -> meas. torque of 59.875Nm and corelosses of 1412W). Apparently the torque calculation is not changing with the number of triangles, where as the core losses decrease with increasing numbers of triangles.
Core Loss Calculation Methods

- Impressed sinusoidal stator currents
  - Simplest Model, fast convergence
- Sinusoidal voltage supply and RL-parameter for winding
  - long Convergence time
- Impressed PWM currents
  - Taken from simulation data, good behavior, medium convergence (2 electrical periods), but needs high resolution
  - Taken from measurement data for verification, needs treatment
- PWM voltage supply model
  - Either in Maxwell or combined with Simplorer.
  - Long simulation time, especially if mechanical model is used.
Results for no load and sinusoidal current excitation

- No load core losses are easy to calculate and have no influence from stator current or PWM Voltage Supply
- Drag losses (for example in an electric rear axle hybrid drive at high speed driving) are important. To calculate the influence of active field weakening at no load is therefore important.
- The Iron Losses decrease with increasing d-current. The Copper Losses increase with increasing d-current. Reduction of 11% of losses with d-current field weakening
Using measured Signal Approach: Noise reduction in measured Signal

Make a sequence of the same signal with a repetition of $2^5$ to increase the resolution of FFT.

Apply FFT and plot Double sided Amplitude Spectrum.

Cut higher frequency harmonics.

Generate the three input currents for Maxwell with corresponding control angle gamma.

Apply inverse FFT and plot Signal.
Core Loss calculation problems in Ansoft 2D

- Core loss computation is treated as "post process" in Maxwell 2D transient, that is, the core loss effects on the field are ignored.
- If the core loss effects on the field are taken into account, when there is a spike in an excitation, the core loss spike will reduce the field change, which in turn reduces the core loss spike.
- In Maxwell 3D transient, we can consider core loss effects on the field.
- Unfortunately, Maxwell 2D transient does not support this at present.

- Results on the right:
  - Core Losses sinusoidal Current: 298W
  - Core Loss PWM Current from Simulation: 866W
  - Core Loss PWM Current from Simulation, only Losses up to 8'000W taken into account: 337W
Conclusions

- Influence of PWM Supply on core losses is an important factor for the efficiency calculation of the motor as all of today's motor are based on PWM supply. In fully optimized systems efficiency gains in the motor due to higher PWM are optimized versus the higher switching losses in the Inverter.
- Iron Loss Calculation becomes an important task in the motor simulation process due to need for efficiency map calculation and optimization over the whole torque and speed range.
- Computational Capabilities are still somehow limited and are based on manufacturer data with limited reliability due to old measurement setups. Manufacturer should modify test equipment to include higher frequencies and additional rotational losses.
- Motor designers are used to 2D simulations to limit simulation time, fully transient simulation including taking into account the influence of eddy currents on the magnetic field should be therefore brought to Maxwell 2D as fast as possible.
**MITRAC**

**Permanent Magnet Motor**

- Environmentally sound use of resources
  - Energy costs per Light Rail Vehicle about 40'000 $US/year (~50t LRV)
  - Energy costs per Metro train about 200’000 $US/year (~230t train)

- Tested and validated, the solution’s innovative motor construction is based on internal permanent magnet technology. It uses a rotor to create its own flux by incorporating magnets. The **MITRAC Internal Permanent Magnet Motor** meets the highest demands on drive systems for traction application.

- Bombardier recently tested the **MITRAC** Permanent Magnet Motor in Sweden. Bombardier replaced four forced air-cooled induction motors in the **BOMBARDIER REGINA** with two of the PM motors as part of the Gröna Tåget (“Green Train”) project.

- The successful tests confirmed that a reduction of two induction motors could be achieved while still providing the same performance for the **REGINA** train.

Research and Development Examples

New SAM: Cree AG, 2009, Switzerland/Poland

Equinox Fuel cell Car, General Motors, USA

ECUV, Sun Ya-Tsen University/HYB, China

Angel Interceptor, Domteknika AG, Switzerland
Electric Motor Glider
ANTARES (Lange Aviation GmbH, Dermany)

Brushless PM-Motor

- Outside runner with phase voltage optimized for block commutation providing best torque density
- high torque (250Nm) at low speed (1’500 prm) and high efficiency (92%) at low mass (28.5kg)
- completely integrated rotor design; rotor acts as case with direct mounted propeller blades
- Air Cooling by large inside diameter
- Series Production by Servax Landert Motoren AG
Thank you very much for your attention

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