Enhancing the Design of Electric Machines through the Interaction of Software Tools

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Enhancing the Design of Electric Machines through the interaction of software tools

**Part I:**
- SPEED and STAR-CCM+
  Enhancing the thermal design of electric machines

**Part II:**
- SPEED and HEEDS
  Optimized design of electric machines
Part I

SPEED and STAR-CCM+
Enhancing the thermal design of electric machines

Enhancing the Design of Electric Machines through the interaction of software tools
SPEED – the design software for electric machines

- Detailed analytical analysis with finite-element links or finite-embedded solver for
  - motors, generators and alternators
  - including inverters and other electronic controls
The **SPEED** software programs

- The following machine types are available:
  - Brushless permanent magnet and wound-field AC synchronous
    - PC-BDC
  - Induction
    - PC-IMD
  - Switched reluctance
    - PC-SRD
  - Direct current (PM)
    - PC-DCM
  - Wound field and PM commutator
    - PC-WFC
SPEED and STAR-CCM+
– ELectrical MAchine Capability (ELMAC)

SPEED

- Analytical calculations
- Geometry templates of electrical machines
- Winding schemes
- Power electronic circuits
- Switch control
- Scripts to drive the EMAG/Thermal calculations

STAR-CCM+

2D/3D EMAG
THERMAL
ELECTRO-CHEMISTRY
BATTERY

ELMAC

2D/3D EMAG
THERMAL
ELECTRO-CHEMISTRY
BATTERY

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Simulation of fluids moving in and around objects
- Liquids and/or gases

Heat transfer
- Conduction
- Convection (natural and forced)
- Radiation

Further Applications
- spray cooling
- oil drip cooling
- ...

Thermal Management Simulation in STAR-CCM+
Temperatures impact life time, reliability, cost & size

Initial analytical design of the electrical machine using SPEED

Reading the SPEED geometry (xGDF) and the loss distribution (*.sbd) file from STAR-CCM+, setting up the CFD 3D model and running the final advanced thermal calculation.

Refinement with PC-FEA
Calculating the performance data on estimated temperatures using PC-FEA to calculate the loss distribution ("Element table") for STAR-CCM+.

Temperatures impact life time, reliability, cost & size
STAR-CCM+ Electrical Machine Capabilities
– Geometry setup

2D to 3D extrusion  Adding end winding  Different rotor types

Different machine types
STAR-CCM+ Electrical Machine Capabilities
– Simplified Winding for Cooling Simulations

Tub end windings for Cooling Simulation for BDC Motor
STAR-CCM+ Electrical Machine Capabilities
– Symmetries and Periodicity
STAR-CCM+ Electrical Machine Capabilities
– Stator and rotor skewing

Stator skewing

Rotor skewing, stepped:
A first STAR-CCM+ EMAG 2D flux density plot with field lines.
Part II

GPS and HEEDS
Optimized design of electric machines with 2 study cases:
(supported by Red Cedar Tech, Mr. Nate Chase)

- **Study 1:**
  Cogging Torque Minimization

- **Study 2:**
  Magnet Volume and Cogging Torque Minimization by keeping the electric motor performance

Enhancing the Design of Electric Machines through the interaction of software tools
HEEDS MDO (Multi-disciplinary Design Optimization)

The main features:

- Multi-disciplinary, multi-objective parametric design optimization
- Automated Design of Experiments (DOE)
- Sensitivity studies
- Robustness and reliability assessments
- Design Sweep (post processing)
  - Create a variety of plots and tables
  - Best illustrate relationships among variables and design goals

Parallel Plot showing design trends among designs evaluated during an optimization.
SPEED Scripting through ActiveX

ActiveX links allows automated linkage to other software packages such as Visual Basic, Matlab, HEEDS and more…
Study 1: Cogging Torque Minimization

Cogging torque
- is due to the interaction between the permanent magnets of the rotor and stator slots of a permanent magnet motor.
- is position dependent
- its periodicity per revolution depends on the number of magnetic poles and the number of teeth on the stator.

Cogging torque can be reduced by:
- Skewing stator stack or magnets
- Using fractional slots per pole
- Optimizing the magnet pole arc or width
- Magnet profiling
- Increase of the air gap
- Decrease slot openings
- Increase radial depth of stator tooth overhangs
- Modulating drive current waveform
Study 1: Cogging Torque Minimization

Baseline Design:
- Cogging Torque = 0.72 Nm
- Magnet Pole Arc ($Beta_M$) = 170°
- Slot Opening (SO) = 3.0 mm
- Air Gap (Gap) = 0.5 mm

Optimized Design:
- Cogging Torque = 0.004 Nm (99% red.)
- Magnet Pole Arc ($Beta_M$) = 123°
- Slot Opening (SO) = 1.15 mm
- Air Gap (Gap) = 1.35 mm

This problem was solved using the default SHERPA search algorithm in HEEDS with 150 evaluations allowed.
Total Runtime = 32.5 minutes on a single CPU, Windows 7 OS, no parallel execution utilized.
A design sweep can be performed after the optimization to generate for example the cogging torque-\(BetaM\) profile for a given configuration:
- Slot Opening (SO) = 1.15 mm
- Air Gap (Gap) = 1.35 mm
- Magnet Pole Arc (\(BetaM\)) = \(100° \text{ to } 180°\)

Plotting the cogging torque vs. \(BetaM\) with the fixed slot opening and air gap reveals two local minima for the cogging torque:
**Study 2: Magnet Volume and Cogging Torque Minimization by keeping the motor performance**

**The goal is to Minimize:**
- Cogging Torque (TVW)
- Volume of the Magnets

**By Varying:**
- \(100° < \text{Magnet Pole Arc (BetaM)} < 180°\)
- \(1 \text{ mm} < \text{Slot Opening (SO)} < 4 \text{ mm}\)
- \(0.3 \text{ mm} < \text{Air Gap (Gap)} < 2 \text{ mm}\)
- \(10 \text{ mm} < \text{Slot Depth (SD)} < 17 \text{ mm}\)
- \(5 \text{ mm} < \text{Tooth Width (TWS)} < 10 \text{ mm}\)
- \(1 \text{ mm} < \text{Magnet Thickness (LM)} < 5 \text{ mm}\)
- \(26 \text{ mm} < \text{Outer Rotor Radius (Rad1)} < 36 \text{ mm}\)
- \(60 \text{ mm} < \text{Stack Length (Lstk)} < 80 \text{ mm}\)
- \(50 \text{ } \leq \text{ Number of Turns per Coil (TC)} \leq 150\)
- \(4 \text{ A} < \text{Current Set Point (ISP)} < 7 \text{ A}\)

Such That:
- \(950 \text{ W} < \text{Shaft Power (Pshaft)} < 1050 \text{ W}\)
- \(190 \text{ V} < \text{Induced Voltage (eLLpk)} < 200 \text{ V}\)
- \(100 \text{ W} < \text{Copper Losses (WCu)} < 120 \text{ W}\)
- \(20 \text{ W} < \text{Iron Losses (WFe)} < 120 \text{ W}\)
- \(1.4 \text{ T} < \text{Stator Tooth Flux Density (Bst)} < 1.6 \text{ T}\)
- \(1.4 \text{ T} < \text{Stator Yoke Flux Density (Bsy)} < 1.6 \text{ T}\)
- \(1.6 \text{ T} < \text{Rotor Yoke Flux Density (Bry)}\)

Where:
- Stator OD (2*Rad3) is 110 mm
- DC link voltage is 300 V, DC frequency is \(f_1 = 66.67 \text{ Hz (2000 rpm, 4 poles)}\)
- Lamination Material is M19-24 gage– NdFeB magnet material is grade 30H (\(Br = 1.12 \text{ T at 20°C}\))

Magnet Volume is calculated as:
\[
\text{Lstk} \times \left(\frac{\text{BetaM}}{360}\right) \times \pi \times \left(\text{Rad1}^2 - \left(\text{Rad1} - \text{LM}\right)^2\right) \text{[unit is mm}^3]\]
### Baseline Design
- Cogging Torque = 1.383 Nm
- Magnet Volume = 18380.9 mm$^3$
- Shaft Power ($P_{shaft}$) = 992.2 W
- Induced Voltage ($eLLpk$) = 197.9 V
- Copper Losses ($W_{Cu}$) = 94.45 W
- Iron Losses ($W_{Fe}$) = 15.31 W
- Total Losses ($W_{Total}$) = 109.76 W
- Stator Tooth Flux Density ($B_{st}$) = 1.58 T
- Stator Yoke Flux Density ($B_{sy}$) = 1.57 T
- Rotor Yoke Flux Density ($B_{ry}$) = 1.25 T

### Optimized Design
- Cogging Torque = 0.0844 Nm (94% reduction)
- Magnet Volume = 9966.6 mm$^3$ (46% reduction)
- Shaft Power ($P_{shaft}$) = 951.2 W
- Induced Voltage ($eLLpk$) = 194.2 V
- Copper Losses ($W_{Cu}$) = 92.12 W
- Iron Losses ($W_{Fe}$) = 12.67 W
- Total Losses ($W_{Total}$) = 104.79 W
- Stator Tooth Flux Density ($B_{st}$) = 1.47 T
- Stator Yoke Flux Density ($B_{sy}$) = 1.54 T
- Rotor Yoke Flux Density ($B_{ry}$) = 0.91 T

This problem was solved
- using the default SHERPA search algorithm in HEEDS with a weighted multi-objective optimization
- with 500 evaluations
- in a total runtime of **1.8 hours**
Study 2: Design Sweep (Post-Optimization)

- 10% Feasible Designs
- 90% Infeasible Designs
Study 2: HEEDS Optimization

- **90% Infeasible Designs**
- **10% Feasible Designs**

Trade-off between volume and cogging torque may be present for best solutions - can investigate using Pareto optimization.
Multi-objective optimizations can be handled with two techniques:

- **Weighted multi-objective** – as was done previously using SHERPA
- **Pareto optimization** – where the goal is to find a set of optimal designs (called a Pareto front). This type of optimization occurs if the objectives are competing: improving the performance of one objective hurts the performance of another

The identical problem was solved again

- using now the Pareto optimization algorithm
- with 2,000 evaluations allowed
- resulting in a total runtime of **7.2 hours**

**Study 2: Pareto Multi-Objective Optimization**
**Study 2: Pareto Multi-Objective Optimization**

After 2,000 evaluations

Design found with weighted multi-objective optimization (not fully converged after the 500 evaluations performed, as is evident here)
Pareto Multi-Objective Optimization

**Baseline Design**

**Concept A Optimized Design:**
94% reduction in cogging torque
52% reduction in magnet volume

**Concept B Optimized Design:**
93% reduction in cogging torque
59% reduction in magnet volume
Part I: SPEED and STAR-CCM+ enhancing the thermal design of electric machines

Part II: SPEED and HEEDS Optimized design of electric machines

Part III: HEEDS with SPEED and STAR-CCM+ Enhancing the Design of Electric Machines through the interaction of software tools