A fast and easy optimization tool for electric rotating machine design

Frigoli Luca Gregorio

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Applicazioni Magnetiche

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Automation Engineer

Working in SPIN Applicazioni Magnetiche since February 2007
Design of electromechanical devices and mechatronics - characterization of magnetic materials
Summary

- Description of the **Best Configuration Searcher**
  - Theoretical aspects
  - Computation software (**SPEED**)  
  - Optimization algorithm (**new CRS**)  
  - Interface

- Explanation of example - **Induction Motor for conveyor belt**
  - Design (parameters, constraints, targets)
  - Results

- Explanation of example - **Torque Motor for electrical propulsion**
  - Design (parameters, constraints, targets)
  - Results

- Conclusions
Best Configuration Searcher

Why...!?

GOALS
IMPROVE THE PERFORMANCES:
- Efficiency
- Power
- Costs
- ...
**Best Configuration Searcher**

- Theoretical aspects

- **User-Friendly Interface**
  - easy to learn
  - precise and clear sequence steps

- **Black Box idea**
  - no programming or macro routine creation are requested
  - the *Algorithm* and *Computation software* create a loop until the best configuration is found
**Best Configuration Searcher**

- Theoretical aspects

**Computation software**

- **SPEED**

  Software based on classical analytical method, so it refers to mathematical equations derived from the electrical machine theory.
SPEED

» Electromagnetic design for electric motors

✓ Brushless Motor
✓ Induction Motor
✓ DC Motor
**Best Configuration Searcher**

- Theoretical aspects

**Algorithm**

- **new Control Random Search (Global Optimization)**

  It’s an algorithm for finding a global minimum/maximum of multimodal an multivariate function. The proposed algorithm is a new version of the well known Price’s algorithm and its distinguishing feature is that it tries to employ as much as possible the information about the objective function obtained at previous iterates.
Best Configuration Searcher

Synchronization

The *Computation software* and the *Algorithm*, during the optimization process, are both opened. They communicate thanks to text files and a particular *Synchronization file* which both read and write.

In this way the optimization process is very fast
Best Configuration Searcher

Interface: main window
Best Configuration Searcher

Analysis Tools

PC-BDC: Sensitivity Analysis
PC-BDC: Table Scanning
PC-BDC: Optimization

Sensitivity Analysis

To verify the robustness of the model, the tolerances influence on the performances

Table Scanning

Search the best configuration in a matrix (Table) defined by the user a priori
Algorithm based on estimated errors or other statistical risk functions

Optimization

Global Optimization in a feasible domain defined by the user (constraint optimization)
new Control Random Search (CRS)
Best Configuration Searcher

Interface: input data

MARCH 19-21, 2012
AMSTERDAM - NETHERLANDS
Best Configuration Searcher

Interface: input data
Best Configuration Searcher

» Interface: input data

✓ Use Sequence Steps

1) Choose model (SPEED File)
2) Check Model
3) Type of analysis
   - Steady State Analysis
   - Static Design
   - Dynamic Design
4) Design:
   - Parameters
   - Constraints
   - Targets
5) Validate Data
6) Run
Best Configuration Searcher

Interface: output data
**Best Configuration Searcher**

- Interface: *output report*

Possibility to save the *Best Model*
Example 1: conveyor belt

Induction Motor

- AC Three Phase
- 4 Poles
- 24 Slots
- 19 Bars

AC Induction Motor: Winding

AC Induction Motor: Section
### Example 1: conveyor belt

Induction Motor

#### Table Scanning

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Min Value</th>
<th>MAX Value</th>
<th>Step Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Radius - Rad1-</td>
<td>mm</td>
<td>20</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Airgap Length - GAP -</td>
<td>mm</td>
<td>0.3</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Number of Turns - TC -</td>
<td></td>
<td>140</td>
<td>150</td>
<td>5</td>
</tr>
<tr>
<td>Stator Outer Radius - Rad3-</td>
<td>mm</td>
<td>50</td>
<td>60</td>
<td>2</td>
</tr>
<tr>
<td>Stator stack length - Lstk -</td>
<td>mm</td>
<td>45</td>
<td>55</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Total Runs: 1620
Example 1: conveyor belt

Induction Motor

Table Scanning

- Constraints

<table>
<thead>
<tr>
<th>Name</th>
<th>Units</th>
<th>Nominal Value</th>
<th>Min Value</th>
<th>MAX Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque - Tshaft -</td>
<td>Nm</td>
<td>0.25</td>
<td>0.22</td>
<td>Inf *</td>
</tr>
<tr>
<td>Copper Losses - WCus -</td>
<td>W</td>
<td>5</td>
<td>0 **</td>
<td>7</td>
</tr>
<tr>
<td>Efficiency - Effcy -</td>
<td>%</td>
<td>75</td>
<td>70</td>
<td>100 *</td>
</tr>
</tbody>
</table>

* It means to **maximize** the variable
** It means to **minimize** the variable
Example 1: conveyor belt

Induction Motor

### Table Scanning

<table>
<thead>
<tr>
<th></th>
<th>Starting Configuration</th>
<th>Best Configuration</th>
<th>delta [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tshaft [Nm]</td>
<td>0.22</td>
<td>0.23</td>
<td>4.5</td>
</tr>
<tr>
<td>WCus [W]</td>
<td>12.4</td>
<td>5</td>
<td>-59.6</td>
</tr>
<tr>
<td>Effcy [%]</td>
<td>63.3</td>
<td>72.5</td>
<td>9.2</td>
</tr>
</tbody>
</table>

- AC Three Phase
- 4 Poles
- 24 Slots
- 19 Bars
Example 2: shipboard electrical auxiliary propulsion

- Torque Motor
  - Three Phase
  - 60 Poles
  - 72 Slots
  - 150 KW

Torque Motor: Section

Diesel Engine

Live Demo
**Example 2:** shipboard electrical auxiliary propulsion

**Torque Motor**

### Optimization

#### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Starting Configuration</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rad3 [mm]</td>
<td>Stator outer radius</td>
<td>250</td>
<td>235</td>
<td>255</td>
</tr>
<tr>
<td>Lstk [mm]</td>
<td>Stack length</td>
<td>400</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td>TC</td>
<td>Turns per coil</td>
<td>30</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>LM [mm]</td>
<td>Length of magnet</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>BetaM [°e]</td>
<td>Magnet pole arc</td>
<td>170</td>
<td>150</td>
<td>175</td>
</tr>
</tbody>
</table>

- Three Phase
- 60 Poles
- 72 Slots
Example 2: shipboard electrical auxiliary propulsion

» Torque Motor

Optimization

- Constraints

<table>
<thead>
<tr>
<th></th>
<th>Starting Configuration</th>
<th>Min Value</th>
<th>Max Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tshaft [Nm]</td>
<td>4518</td>
<td>4500</td>
<td>4600</td>
</tr>
<tr>
<td>Torque</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jrms [A/mm²]</td>
<td>23.65</td>
<td>0*</td>
<td>20</td>
</tr>
<tr>
<td>Current Density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wt_Tot [Kg]</td>
<td>421.5</td>
<td>0*</td>
<td>400</td>
</tr>
<tr>
<td>Total Weight</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*It means to minimize the variable
Example 2: shipboard electrical auxiliary propulsion

» Torque Motor

Optimization

Targets

Starting Configuration

- Eff [%]
- Efficiency
- 85.44

Maximize

- Three Phase
- 60 Poles
- 72 Slots
Example 2: shipboard electrical auxiliary propulsion

Torque Motor

Results

Optimization

- Three Phase
- 60 Poles
- 72 Slots

Static Design
- new CRS
- 463 runs
- ~ 5 min
Example 2: shipboard electrical auxiliary propulsion

**Torque Motor**

Results

<table>
<thead>
<tr>
<th>Optimization</th>
<th>Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization</td>
<td>Optimization</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Starting Configuration</th>
<th>Best Configuration</th>
<th>delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tshaft [Nm] Torque</td>
<td>4518</td>
<td>4537</td>
<td>--</td>
</tr>
<tr>
<td>Jrms [A/mm²] Current Density</td>
<td>23.65</td>
<td>19.5</td>
<td>- 17 %</td>
</tr>
<tr>
<td>Wt_Tot [Kg] Total Weight</td>
<td>421.5</td>
<td>398.3</td>
<td>- 5.5 %</td>
</tr>
<tr>
<td>Eff [%] Efficiency</td>
<td>85.4</td>
<td>88.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Example 3: military application

» Brushless generator slotless

2 Poles on a ring magnet
Example 3: military application

» Brushless generator slotless

Software based on finite-element method (FEM)
Example 3: military application

- Brushless generator slotless

- BCS Optimization

- Yes

- FLUX Model

- Similar results?

- NO

- Calibration of SPEED Model

- Yes

- End of computation
Example 3: military application

Brushless generator slotless

Step 0: Calibration of SPEED Model

<table>
<thead>
<tr>
<th>Name</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Radius - Rad1-</td>
<td>mm</td>
<td>21</td>
</tr>
<tr>
<td>Stator Outer Radius - Rad3-</td>
<td>mm</td>
<td>36</td>
</tr>
<tr>
<td>Slot Depth - SD -</td>
<td>mm</td>
<td>5.3</td>
</tr>
<tr>
<td>Length of magnet - LM -</td>
<td>mm</td>
<td>5.5</td>
</tr>
<tr>
<td>Number of Turns - TC -</td>
<td></td>
<td>76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SPEED model</th>
<th>FLUX Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jrms [A/mm²] Current Density</td>
<td>132</td>
<td>50</td>
</tr>
<tr>
<td>Eff [%] Efficiency</td>
<td>68</td>
<td>86.4</td>
</tr>
</tbody>
</table>

Calibration of SPEED Model

<table>
<thead>
<tr>
<th></th>
<th>SPEED model</th>
<th>FLUX Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jrms [A/mm²] Current Density</td>
<td>48.9</td>
<td>50</td>
</tr>
<tr>
<td>Eff [%] Efficiency</td>
<td>87.2</td>
<td>86.4</td>
</tr>
</tbody>
</table>
Example 3: military application

Brushless generator slotless

- Step 1: BCS Optimization

<table>
<thead>
<tr>
<th>Starting Configuration</th>
<th>Min Value</th>
<th>Max Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jrms [A/mm²] Current Density</td>
<td>48.9</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Starting Configuration</th>
<th>Eff [%] Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>87.2</td>
</tr>
</tbody>
</table>

Maximize
Example 3: military application

Brushless generator slotless

Step 2: Comparison Results

<table>
<thead>
<tr>
<th>Name</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Radius - Rad1-</td>
<td>mm</td>
<td>38.2</td>
</tr>
<tr>
<td>Stator Outer Radius - Rad3-</td>
<td>mm</td>
<td>58</td>
</tr>
<tr>
<td>Slot Depth - SD -</td>
<td>mm</td>
<td>8.5</td>
</tr>
<tr>
<td>Length of magnet - LM -</td>
<td>mm</td>
<td>5.5</td>
</tr>
<tr>
<td>Number of Turns - TC -</td>
<td></td>
<td>44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SPEED model</th>
<th>FLUX Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jrms [A/mm²] Current Density</td>
<td>9.9</td>
<td>12.2</td>
</tr>
<tr>
<td>Eff [%] Efficiency</td>
<td>96.8</td>
<td>93.7</td>
</tr>
</tbody>
</table>

End of computation
Example 3: military application

- Brushless generator slotless

<table>
<thead>
<tr>
<th>Optimization</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Starting Configuration</th>
<th>Best Configuration</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPEED model</strong></td>
<td><strong>FLUX model</strong></td>
<td><strong>SPEED model</strong></td>
</tr>
<tr>
<td>Jrms [A/mm²] Current Density</td>
<td>48.9</td>
<td>50</td>
</tr>
<tr>
<td>Eff [%] Efficiency</td>
<td>87.2</td>
<td>86.4</td>
</tr>
</tbody>
</table>
Example 3: military application

- Brushless generator slotless

![Diagram showing an example of a brushless generator slotless system with magnetic fields marked N and S, and a graph indicating the mean value of 1.9 Nm.]
Best Configuration Searcher

Conclusions

This type of tools can be very useful in electromagnetic motor design:

- fast and intuitive
- possible to analyze many different configurations in a very short time
- automate a series of tasks often performed in a very tedious and long procedure
- choosing the best configuration with a more appropriate optimization

![Diagram with icons and text boxes: less time, cost reduction, more efficiency]
A fast and easy optimization tool for electric rotating machine design

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21/3/2012

THANKS FOR YOUR ATTENTION

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