Numerical multi-objective optimization of an innovative totally enclosed fan cooled induction motor

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OUR GOAL

Maximize the power installed on a TEFC (Totally Enclosed Fan Cooled) induction machine of a certain frame size and respecting the API & SHELL performance and technical constraints.

Engineering target: **Specific power cost minimization** $[\text{\euro/kW}]$ of Oil & Gas Market motors
CURRENT TEFC PERFORMANCE

Starting point

CA 450 L4

Active parts length = 840mm

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power@1500rpm</td>
<td>800kW</td>
</tr>
<tr>
<td>Voltage</td>
<td>6600V</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.86</td>
</tr>
<tr>
<td>Rated current</td>
<td>89A</td>
</tr>
<tr>
<td>Efficiency</td>
<td>96.3%</td>
</tr>
<tr>
<td>Locked rotor current (LRC)</td>
<td>560%</td>
</tr>
<tr>
<td>Locked rotor torque (LRT)</td>
<td>60%</td>
</tr>
</tbody>
</table>
LIMITS OF TEFC MOTOR STRUCTURE

Radial heat flow
convective physical limitation

Rotor and stator additional
losses amplitude

Rotor and stator
constrained dimensions

Rotor axial cooling flow limitation
New concepts introduced to overcome current TEFC limits and design the **NEW TEFC**

- External pipes instead of recirculation pockets (stat/rot heat flux decoupling).
- Forced pipes and fins cooling with external carter.
- High number of fins with single-side welding.
- Exchange surfaces high temperature.
- Rotor copper bars with cryogenic insertion.
- Closed rotor slot.
- Inter-bar axial rotor cooling channels.
- Increased fans power.
Performance prediction needs sharp design tools for design improvement

Current IM design tool is analytical and empirically corrected with tested machine results; does not take into account precisely of field distribution (current, magnetic field)

To overcome this limitations:

- Wide R&D team effort to develop a novel performance forecast tool ('IDaphne' software).
- Industrial solution identification by means of Multi-Objective optimization and Genetic Algorithm (MOGA).
IDaphne → completely new hybrid analytical / 2D finite elements analysis approach to take care of:

- Magnetic and current **fields distribution** (they are both functions of current amplitude and frequency)
- Heat flow distribution
- Local non linear materials behaviour
This complex approach has **two big advantages**: it is **more accurate** than the standard approach and permits targeting the absolute maximum result.
OPTIMIZATION WORKFLOW

**ModeFrontier®**

**INPUT**
(geometry parameters)

**solving (iDaphne)**

**OUTPUT**
(e.m., thermal, dimensions)

**PROBLEM CONSTANTS**

**CONSTRAINS**

**OBJECTIVES**
(€/kW, max. temp.)

Automatic loop: changes the value of the input parameters on the basis of the previous results.
CHOICE OF THE OPTIMUM DESIGN

Obj 2: Minimize Maximum copper temperature

160.5: temp. limit

Minimize €/kW

Industrial Optimum
NEW TEFC OUTPUT RESULTS – 2D MAGNETIC FEA

- No Load
- Locked rotor
- Rated
**NEW TEFC OUTPUT RESULTS – PERFORMANCE**

**CAT 450 L4**

<table>
<thead>
<tr>
<th>Description</th>
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</tr>
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<tbody>
<tr>
<td>Rated power@1500rpm</td>
<td>1900kW</td>
</tr>
<tr>
<td>Slip</td>
<td>0.84%</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.88</td>
</tr>
<tr>
<td>Rated current</td>
<td>194A</td>
</tr>
<tr>
<td>Efficiency</td>
<td>97.4%</td>
</tr>
<tr>
<td>Locked rotor current (LRC)</td>
<td>600%</td>
</tr>
<tr>
<td>Locked rotor torque (LRT)</td>
<td>96%</td>
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### Specific Losses [W/m³]

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Losses [W/m³]</th>
<th>Thermal conductivity [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoke</td>
<td>28811.5</td>
<td>30</td>
</tr>
<tr>
<td>Tooth</td>
<td>37927</td>
<td>30</td>
</tr>
<tr>
<td>Copper</td>
<td>198091</td>
<td>380</td>
</tr>
<tr>
<td>Insulation</td>
<td>-</td>
<td>0.15</td>
</tr>
</tbody>
</table>
External reference air temp. = 308K (35°C)

End winding max temp. = +122K

Max rotor bar temp. = +130K

Average winding temp. = +80K

External air flow

Internal air flow
External cooling pipes instead of recirculation pockets (same dissipating surface but double average convection coefficient) patent applied (EU 14163634.0)

Increased global heat exchange surface (+47%)

Increased exchange temperature for better exploitation of the cooling tubes (+10K)

Increased inner and outer cooling flows (+40%)
Subcritical behaviour up to 2100rpm

45% separation margin with respect to 1800rpm (rated speed)
## PERFORMANCE COMPARISON

**TEFC (CA 450 L4) VS. NEW TEFC (CAT 450 L4)**

Active parts length 840mm  
Active parts length 1000mm

<table>
<thead>
<tr>
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<td>96%</td>
</tr>
<tr>
<td>Weight</td>
<td>4000kg</td>
<td>6500kg</td>
</tr>
</tbody>
</table>

**COST REDUCTION**  
-31.5%  
5 kg(≡$)/kW  
3.4 kg(≡$)/kW
Thank you for your attention