A conceptual design and analysis of a 5MW HTS motor for future electric aircraft

Presenter: Dinh-Vuong Le*

G.-D. Nam, B.-S. Go, S.-J. Lee and M. Park†

Changwon National University
(†capta.paper@gmail.com)
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World airport passengers

- Airport passengers are increasing rapidly.
- Combustion engine has a large emission gas, noise, and releases large heat → it can cause the significant effects to the Earth.

→ Preparing for a revolution in the aviation industry
1. Introduction

Current status of propulsion systems in the aircrafts

Thermopropulsive (overall) efficiency

State-of-art:
Thermodynamic efficiency: ~ 55%
Propulsive efficiency: ~ 72%
Overall efficiency: ~ 39.6%
(Less than a half!)

Efficiency of the propulsion system is combined of efficiency of thermodynamic efficiency (burn fuel) and propulsive efficiency (shaft power to thrust by fan/propeller)
Configuration of electric propulsion systems

1. Introduction

Large power capacity turbine engines to generate electric power \(\rightarrow\) keep the thermodynamic efficiency at reasonable value.

**Thermopropulsive (overall) efficiency**

- Thermodynamic efficiency: \(\sim 55\%\)
- Propulsive efficiency: \(72\% \rightarrow 90\%\)

**BPR: 15 ~ 20**

\[ \text{LH}_2 \]

**G**

**High speed generator**

**Turboshaft engine**

- **Fuel**

Electric motor has high efficiency that is not depend on the power capacity, relatively.

**Electric propulsion motor** is proposed to overcome the drawback of the small/medium capacity turbine engines.

Electricity production can be configured in other configurations.
The power capacity of electric propulsion motor was limited by the disadvantages of the conventional motor (power density).
Conventional motor (volume/weight/power density limitation) is not suitable for the large electric aircrafts → Superconductivity opens a new era for the electrical aircrafts
Propulsion system architecture

2. Design of a 5 MW HTS motor

- **Source**
  - Fuel
  - LH₂
  - Battery
- **Thermal efficiency**
  - Conventional: 55%
  - Turboelectric: 55%
  - Fuelcell electric: 62%
- **Propulsive efficiency**
  - G → AC/DC → DC/AC → M → Fan
  - Efficiency: 99%
- **Overall**
  - Fan
  - ~39.6%
  - ~47.6%
  - ~54.1%
  - ~87.3%

High efficiency, high specific power (kW/kg) machine plays a key role

To analyze the effect of motor parameters on specific power, the 5 MW HTS motors were designed with five different pole numbers (4, 6, 8, 12, and 16 poles) and two different effective lengths (150 mm and 300 mm). Other parameters were kept at constant.

### Parameters of rotor part

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS wire thickness</td>
<td>12 mm</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>30 K</td>
</tr>
<tr>
<td>Operating current</td>
<td>490 A</td>
</tr>
<tr>
<td>(I_o/I_c) ratio</td>
<td>0.7</td>
</tr>
<tr>
<td>Minimum bending diameter of the HTS wire</td>
<td>60 mm</td>
</tr>
<tr>
<td>Distance between two rotor poles</td>
<td>30 mm</td>
</tr>
<tr>
<td>Number of turn/layer of HTS coil</td>
<td>85 turn</td>
</tr>
<tr>
<td>Total air gap of the motor</td>
<td>15 mm</td>
</tr>
<tr>
<td>Material of the rotor body</td>
<td>Al6061</td>
</tr>
</tbody>
</table>

### Parameters of stator part

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phase</td>
<td>9</td>
</tr>
<tr>
<td>Number of slot/pole</td>
<td>9</td>
</tr>
<tr>
<td>Current density</td>
<td>5.8 A/mm²</td>
</tr>
<tr>
<td>Maximum magnetic flux density outside the stator shield</td>
<td>1.42 T</td>
</tr>
<tr>
<td>Stator wire</td>
<td>Copper-Litz</td>
</tr>
<tr>
<td>Winding method</td>
<td>Overlap</td>
</tr>
<tr>
<td>Material of teeth</td>
<td>M47-26Ga</td>
</tr>
<tr>
<td>Material of stator shield</td>
<td>M47-24Ga</td>
</tr>
</tbody>
</table>
2. Design of a 5 MW HTS motor

Weight comparison of several HTS motor designs

- The design of 8-pole or 12-pole, effective length of 150 mm has lightest weight.
2. Design of a 5 MW HTS motor

Specific power comparison of several HTS motor designs

- The 12-pole with an effective length of 150 mm produced the highest specific power of 18.04 kW/kg.
2. Design of a 5 MW HTS motor

Weight comparison of several HTS motor designs

- Weight proportion of copper reduces along with no. of pole (MMF of field coil increase)
- Weight proportion of the stator shield and HTS module increase by increasing of no. of pole & motor diameter
### Specifications of the 5 MW HTS motor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pole</td>
<td>12</td>
</tr>
<tr>
<td>No. of phase</td>
<td>9</td>
</tr>
<tr>
<td>Effective length</td>
<td>150 mm</td>
</tr>
<tr>
<td>Rotor inner radius</td>
<td>316.0 mm</td>
</tr>
<tr>
<td>Stator outer radius</td>
<td>400.45 mm</td>
</tr>
<tr>
<td>Stator inner radius</td>
<td>364.0 mm</td>
</tr>
<tr>
<td>Total air gap</td>
<td>15.0 mm</td>
</tr>
<tr>
<td>Rotor pole width</td>
<td>163.57 mm</td>
</tr>
<tr>
<td>HTS winding width</td>
<td>97.57 mm</td>
</tr>
<tr>
<td>Magnetic shield thickness</td>
<td>18.0 mm</td>
</tr>
<tr>
<td>Slot depth</td>
<td>8.45 mm</td>
</tr>
<tr>
<td>Support width</td>
<td>30.0 mm</td>
</tr>
</tbody>
</table>
Detailed design of the 5 MW HTS motor

Specifications of the 5 MW HTS motor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS wire</td>
<td>12 x 0.15 mm</td>
</tr>
<tr>
<td>Insulation</td>
<td>No-insulation</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>30 K</td>
</tr>
<tr>
<td>Operating current</td>
<td>490 A</td>
</tr>
<tr>
<td>Rotor body material</td>
<td>Al6061</td>
</tr>
<tr>
<td>Stator teeth and shield</td>
<td>Iron silicon steel</td>
</tr>
<tr>
<td>materials</td>
<td></td>
</tr>
<tr>
<td>Stator current density</td>
<td>5.8 A/mm²</td>
</tr>
</tbody>
</table>

Bending diameter of the HTS wire was selected to 60 mm that is double of minimum values.
3. FEM simulation results

**Electromagnetic simulation results**

**Magnetic field distribution at full-load condition**

- **Magnetic shield**: 1.502 T
- **Stator teeth**: 2.513 T
- **Copper coil**: 0.301 T

Maximum magnetic field on HTS wire: 2.48 T

- **Magnetic shield**: 1.45 T
- **Stator teeth**: 0.79 T
- **Copper coil**: 0.139 T

Maximum magnetic field on HTS wire: 1.98 T

The maximum magnetic field of the motor is **2.513 T** at the stator teeth and HTS winding. The maximum perpendicular magnetic field on the HTS winding is about **1.93 T**.
3. FEM simulation results

Analysis of the motor weight

Weight of motor components

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor body</td>
<td>30.629 kg</td>
</tr>
<tr>
<td>HTS module</td>
<td>35.1 kg</td>
</tr>
<tr>
<td>Stator shield</td>
<td>97.97 kg</td>
</tr>
<tr>
<td>Stator teeth</td>
<td>56.94 kg</td>
</tr>
<tr>
<td>Copper winding</td>
<td>58.71 kg</td>
</tr>
<tr>
<td>Error</td>
<td>10%</td>
</tr>
<tr>
<td>Total weight of motor</td>
<td>307.19 kg</td>
</tr>
<tr>
<td>Specific power</td>
<td>16.28 kW/kg</td>
</tr>
</tbody>
</table>

The specific power of the motor is about **16.28 kW/kg** (without cooling system).

The stator part accounts for **74% of the total motor weight** → it is certain that reducing the weight proportion of the stator part will be a shortcut to greatly improving the specific power of the motor.
Comparison of the specific power

- **Power:** 2.5 MW
  - RPM: 20,000
  - 16.66 kW/kg

- **Power:** 5 MW
  - RPM: 7200
  - 16.28 kW/kg

- **Power:** 1-5 MW
  - RPM: 2500-5400
  - 8-17 kW/kg

- **Power:** 10 MW
  - RPM: 6,000
  - 25 kW/kg

- **Ship motor:** 4.0 MW
  - RPM: 120
  - 0.11 kW/kg

- **Ship motor:** 3.725 MW
  - RPM: 1800
  - 0.745 kW/kg

- **HV series**
  - RPM: 1780-1880

- **0.13 ~ 0.65 kW/kg**
Conclusions

- This paper presents a conceptual design and analysis results of a 5 MW HTS motor for future electric aircraft.

- Several designs for the 5 MW HTS motor were evaluated. Among them, the design of 12-pole, the effective length of 150 mm had the highest specific power of 16.28 kW/kg, which is three times higher than conventional motors.

- The efficiency of 97.37% was achieved. The power loss caused by eddy current loss was significant.

- The weight proportion of the stator part accounts for 74% of the total weight of the motor. Improvement of the stator part will be focused for future work.

Acknowledgement

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Thank you for your attention