Electric propulsion components with high power densities for aviation
The world is becoming electric – in aviation as well

We develop serial hybrid electric propulsion systems for aircraft

The technology is scalable and will soon be making its way into small aircraft and, in the future, into commercial aircraft with 60 to 100 passengers, making aviation 'greener'.

Aviation optimization possibilities thanks to electric propulsion are

• Less or no fuel consumption and pollution by using hybrid or full electric drives
• Increase of aerodynamic efficiency of aircraft by distributed propulsion
• Silent propulsion for night starts and landings
• Lower operation costs (fuel, maintenance)
• Safety increase with redundant energy sources

Motivation of these days:
80 kW propulsion in flight
Fuel consumption has high share (~ 51%) of aircraft total cost of ownership

Reduction of fuel consumption is main lever to reduce aircraft TCO

Note: Calculated using hourly operational costs from September 2007 Form 41 data for all US carriers currently operating 737-800s (Continental, American, Delta, Sun Country, ATA, Alaska). Assumes uptime avg. 10.3 block hrs/day, 20-year lifecycle, and 8-10 year modification cycle.

Source: Carrier Form 41 reports, IATA, airfinancejournal.com, TeamSai, Aerostrategy; BCG
### Challenges: Light construction, Safety, Certification & Integration

<table>
<thead>
<tr>
<th>Propulsion</th>
<th>light, efficient, reliable &amp; safe, silent</th>
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</thead>
<tbody>
<tr>
<td>E-machine</td>
<td>&gt; 95 %</td>
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<td></td>
<td>&gt; 6 kW/kg</td>
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<tr>
<td>Inverter</td>
<td>&gt; 20 kVA/kg</td>
</tr>
<tr>
<td>Controls</td>
<td>safe and redundant (HW, SW)</td>
</tr>
<tr>
<td>Cooling</td>
<td>Light, small and adapted to airframe</td>
</tr>
<tr>
<td>Combustion engine</td>
<td>light, low consumption and emissions</td>
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<td>Energy storage</td>
<td>safe, integrated with airframe, light, optimized for energy or power density (depending on application)</td>
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</tbody>
</table>

**Propulsion**
- **P_{mech}**: 0.66 MW continuous
- **Power density**: 0.87 kW/kg

**Controls**
- Scalable
- **Power density**: 5 kW/kg

**Inverter**
- > 20 kVA/kg

**Cooling**
- Light, small and adapted to airframe

**Combustion engine**
- Light, low consumption and emissions

**Energy storage**
- Safe, integrated with airframe, light, optimized for energy or power density (depending on application)
Roadmap of our development projects

Siemens hybrid electric propulsion systems for aircraft

- LSA (DA36 eStar Generation 2)
- Propeller aircraft
- Regional aircraft, 60-100 seats

Maturity phase production
Product development
Prototyping and design studies
Initial concepts

- 2011-2014
- today-2016
- 2019
- 2025
- > 2035
Milestones

2011

2013

2014

2015
Application: DA 36 E-Star 2
Motor Glider Propulsion System
Maiden Flight 01. June 2013

- Developed in cooperation with Compact Dynamics
- Serial hybrid electric aircraft with same payload and range as standard aircraft

Key data

\[ P_{180s} = 80 \text{ kW} \]
\[ N_{\text{max intern}} = 11000 \text{ rpm} \]
\[ M_{180s} = 70 \text{ Nm} \]
\[ N_{\text{max shaft}} = 2400 \text{ rpm} \]
Liquid cooled

\[ P_{\text{cont.}} = 65 \text{ kW} \]
weight = 13 kg
~ 5 kW / kg
including inverter & gearbox
Milestones

2011

2013

2014

2015
¼ MW electric motor for aircraft propulsion put into operation in January 2015

Electric Motor Performance
- Successfully tested at a continuous mechanical power of 261 kW at 2500 rpm
- Excellent thermal behavior
- Motor can drive propeller directly without gearbox
- Motor was developed for aircraft application
- Motor design is scalable towards 1 MW

This is the strongest motor, ever built with a power density of 5 kW/kg
1/4 MW electric motor has been developed in application project in LUFO IV

Design data

\[ P_{\text{cont}} = 230 \text{ kW} \]
\[ N_{\text{nom}} = 2250 \text{ rpm} \]
\[ M_{\text{cont}} = 977 \text{ Nm} \]
\[ U_{ZK} = 580 \text{ V} \]
\[ I = 2 \times 218 \text{ A} \]
\[ \eta_{230kW} > 95\% \]

Tested on bench

\[ P_{\text{cont}} = 261 \text{ kW} \]
\[ N_{\text{max}} = 2500 \text{ rpm} \]
\[ M_{\text{cont}} = 1000 \text{ Nm} \]
\[ \eta_{260kW} = 95\% \]

- 2 redundant winding systems
- Direct cooling with \( T_{\text{inlet}} = 90 \, ^\circ\text{C} \)
- Integrated propeller bearing

- Motor with prop. bearing = 50 kg
- Power density > 5 kW/kg
- Dimensions:
  \[ D = 418 \text{ mm}, \ L = 300 \text{ mm} \]
  (w/o prop. bearing)
Steps to achieve a light weight E-Motor design I

1. Electromagnetic design with high performance magnetic materials to the edge of physical boarders
   - High electric frequency
e   - to achieve highest torque density
   - Flat wire windings
   - Smart magnetic circle using Halbach array

2. Highly performing cooling
   - Major losses are copper losses, therefore direct cooling
     → continuous current density significantly higher than usual
   - High coolant temperature level (90-100 ºC) is possible, which minimizes cooler size and weight
3. Structural weight optimization of passive parts

- e.g. bearing plate: from 10.5 kg down to 4.9 kg
- Machined structural parts made of light weight materials (Aluminum) instead of cast iron design
- Strength calculations to meet aircraft requirements
- Use of CFK structural parts have potential for further weight reduction
Serial hybrid electric propulsion systems for aircraft under development

**Generator sets in development**
- 100 kW compatible with Rotax 912 and Rotax 914
- 135 kW compatible with AE300
- 170 kW
- 10 MW (HTSC)

**Serial hybrid electric propulsion system with two redundant power paths**

**Propulsion systems in development**
- 60 - 120 kW for different voltage levels
- 200 kW - 260 kW
- 600 kW
- 1 MW

- 100 kW compatible with Rotax 912 and Rotax 914
- 135 kW compatible with AE300
- 170 kW
- 10 MW (HTSC)
170 kW Generator
Lab Approval

Design data

- Redundant winding system
- Each one can be overboosted for 3 minutes
- Usage as motor or generator possible
- Direct cooling
- Mechanical design for direct coupling to ICE or gearbox (including propeller bearing) mounting
- Dimensions: D = 308 mm, L = 150 mm
- Weight: 24.4 kg → 7 kW/kg (electric machine only)

\[ P_{\text{cont}} = 170 \text{ kW} @ 6250 \text{ rpm} \]
\[ N_{\text{max}} = 6500 \text{ rpm} \]
\[ M_{\text{cont}} = 260 \text{ Nm} \]
\[ U_{ZK} = 580 \text{ V}, I = 2 \times 131 \text{ A} \]
\[ \eta_{170\text{kw}} > 95 \% \]
To close with a joke…

This is not the speed sensor of the load generator… This is the 260kW motor.
Electric Propulsion for Aircraft

Direct drive ¼ MW scalable to 1 MW

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