High Field Superconducting Machines

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Comment from a reviewer:

“This is, by now, a very old technology that has not yet found a place in society. Why are you beating this 30 year's old dead horse?”
Overview

SC rotating machine landscape, barriers to adoption

Opportunities
- high field motors for aircraft based on MRI technology

Extension to wind

Discussion
Technically Feasible
Superconducting Machines at GE

1970's – 1980's (LTS)
Commercial 20 MVA superconducting generator, 4K, liq. He, NbTi

Military 20 MW generator, 4.5/8 Kelvin - NbTi/Nb3Sn

DC homopolar propulsion motor. 3000 hp, 1200rpm

1990's – 2000's (HTS)
1.5 MVA HTS generator demonstrator built and tested
Design of 100 MVA HTS generator for utility applications

1.7MW, HTS, 40K Hydrogenerator

5MW HTS-HIA generator, 30K – YBCO, 35000 rpm. 4MW demo tested at 10,500 rpm
Challenge: Need to improve perceived value vs risks/costs

Is there a “Killer App” for SC Machines?
- “only superconducting solution makes the system viable”

Would the following come close to meeting this criteria?
- Industrial Motors
- Utility Generators
- Ship propulsion motors
- Wind turbine generators
- Electric drives for aircraft
45 MW Turbo-Electric Distributed Propulsion (TEDP): NASA N3-X

45 MW Electrical Drivetrain – 1st order estimate

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Cu Wire or PM @ 293K</th>
<th>All-Superconductor or Cryogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor/Generator Power Density (kW/kg)</td>
<td>3 - 7</td>
<td>40 - 65</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>85 %</td>
<td>99 %</td>
</tr>
<tr>
<td>Heat Loss</td>
<td>6.8 MW</td>
<td>0.45 MW</td>
</tr>
<tr>
<td>Mass</td>
<td>146 klb</td>
<td>11 klb</td>
</tr>
<tr>
<td>TRL Level - Airborne</td>
<td>9</td>
<td>1 - 3</td>
</tr>
</tbody>
</table>

Erases gains from HEDP drag reduction

Higher than payload = 118 klb!

Cryogenics enabling technology for HEDP

J. Felder et al, NASA-Glenn, ISABE_2011_1340
Benefits versus cost + risk

Induction machine

Hydrogenie from GE

Jet Engine

Rolls Royce Trent 700 engine


http://aviaHonnewsportal.com/
NASA's Fundamental Aeronautics Program addresses national challenges in air transportation by enabling advanced technologies that will improve the performance and environmental impact of future air vehicles. Projects: Fixed Wing, Rotary Wing, High Speed, Aeronautical Sciences.

**THE FIXED WING PROJECT**

Fixed wing research includes exploring and developing tools, technologies and concepts for vastly improved energy efficiency and environmental compatibility necessary for the sustained growth of commercial aviation vital to the U.S. economy and quality of life.

<table>
<thead>
<tr>
<th>Theme</th>
<th>TC Title</th>
<th>TC Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighter-Weight, Lower-Drag Fuselage</td>
<td>Fuselage Structural Weight</td>
<td>Reduce fuselage structural weight by 15% with neutral or positive drag impacts while not affecting certification and passenger comfort (TRL4)</td>
</tr>
<tr>
<td>Higher Aspect Ratio Optimal Wing</td>
<td>Optimal Aspect Ratio</td>
<td>Enable a 1.5-2X increase in the optimal wing aspect ratio with certifiable structures and flight control (TRL 3)</td>
</tr>
<tr>
<td>Quieter Low-Speed Performance</td>
<td>Community Noise</td>
<td>Reduce perceived community noise by 12 dB cum with minimal impact on weight and performance (TRL5)</td>
</tr>
<tr>
<td>Cleaner, Compact, Higher Bypass Ratio Propulsion</td>
<td>Low NOx, Fuel-Flex Combustor</td>
<td>Reduce NOx emissions from fuel-flexible combustors to 80% below the CAEP6 standard with minimal impacts on weight, noise, or component life (TRL3)</td>
</tr>
<tr>
<td>Cleaner, Compact, Higher Bypass Ratio Propulsion</td>
<td>Compact, High OPR Gas Generator</td>
<td>Enable reduced size/flow gas generators with 50+ OPR and disk/seal temperatures of 1500F with minimal impact on noise and component life (TRL4)</td>
</tr>
<tr>
<td>Hybrid Gas-Electric Propulsion</td>
<td>Electric Motor Power Density</td>
<td>Achieve a 2X increase in the power density of an electric motor (TRL 3)</td>
</tr>
<tr>
<td>Unconventional Propulsion-Airframe Integration</td>
<td>Integrated Boundary-Layer Ingestion System</td>
<td>Achieve a vehicle-level net system benefit with a distortion-tolerant inlet/fan, boundary-layer ingesting propulsion system on a representative vehicle (TRL3)</td>
</tr>
<tr>
<td>Alternative Fuel Emissions</td>
<td>Alternative Fuel Emissions at Cruise</td>
<td>Fundamental characterization of a representative range of alternative fuel emissions at cruise altitude</td>
</tr>
</tbody>
</table>
NASA FW/AATT HEP Technology Roadmap

**MW Size Motors**
- 4 hp/lb (6.6 kW/kg), partially superconducting
  - Today
  - 8 hp/lb (13.2 kW/kg)
  - 2020
  - 10 hp/lb (16.5 kW/kg)
  - 2025
  - 12 hp/lb (19.7 kW/kg)
  - 2030
  - Non-Cryogenic
  - 2035

**Cryogenic, Superconducting**
- 2X increase in power density
- 5X increase in power density
- 10X increase in power density

**Power Electronics**
- 2X decrease in weight
- 5X decrease in weight
- 10X decrease in weight

**Power Transmission System**
- Perf. and control system verification in KW scale
- Perf. and control system verification in MW scale
- Subscale flight test

**Electric Propulsion-Aircraft Integration**
- Distributed electric propulsion performance and control

**Increase in power density and reduction of weight of other electrical components**

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Fixed Wing Project
Fundamental Aeronautics Program

ECE ILLINOIS
Wound Field Synchronous Machines

Electrical machine power density:

\[ P_R = \frac{1}{1 + K_D \frac{m}{m_i} \frac{\tilde{n}}{2} K_I K_p \eta B_g A f} \ \lambda^2 \delta^2 L_e. \]

Maximize electrical loading, magnetic loading, and rotor tip speed - simultaneously!

If rpm and diameter limited (e.g. wind generators) => maximize torque density.

Available Conductors

The National High Magnetic Field Laboratory
High Field Superconducting Motor

NASA LEARN Phase 1: Establish feasibility of superconducting motor with:
• Stationary field winding assembly to utilize MRI technology
• Explore peak fields up to 10T
• Active magnetic shield to eliminate field outside while maximizing "air gap" flux density
• High field superconductor (e.g. Nb$_3$Sn)
Electromagnetics

Flux density distribution in a cross section of the machine with an active EM shield.

Radial Flux Density along D-axis

Flux density distribution in a cross section of the machine with a passive ferromagnetic shield.

Radial Flux Density at Armature
Optimization – First pass

Pareto-Optimal Front for Nb$_3$Sn Tube-Type

<table>
<thead>
<tr>
<th>Key Design Parameters</th>
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<tbody>
<tr>
<td>Output Power</td>
<td>10 MW</td>
</tr>
<tr>
<td>Speed</td>
<td>3000 rpm</td>
</tr>
<tr>
<td>Maximum External Field</td>
<td>0.5 mT</td>
</tr>
<tr>
<td>LTS Critical Surface Safety Margin</td>
<td>50%</td>
</tr>
<tr>
<td>HTS Critical Surface Safety Margin</td>
<td>80%</td>
</tr>
<tr>
<td>Rotor Tip Speed</td>
<td>95 m/s</td>
</tr>
<tr>
<td>Electrical Loading</td>
<td>1700 A/in</td>
</tr>
</tbody>
</table>

Critical current density above 15 MA cm$^{-2}$ at 30 K, 3 T in 2.2 $\mu$m thick heavily-doped (Gd,Y)Ba$_2$Cu$_3$O$_x$ superconductor tapes

Initial analysis with conservative electrical loading and rotor tip speed

Comparison with YBCO
Key Technical Challenges

Cryogenic Thermal Management System
- reliability, cryogen free?

High field SC coils, stability
- Racetrack coils, cyclic torques, ac losses, ramps

Structural integrity

Overall motor configuration
Cooling System

Key Design Considerations:
• Heat loads: torque tube, radiation, current leads
• Most efficient cooling at ~4-10K
• Borrow best practices from prior cryogen free cooling schemes
Heat Loads

Heat loads for current baseline design
Cryocooler Stage 1
Radiation: 31.74W
Conduction w/ TT: 23.06W
Current Leads: 13.9W
Total: 68.7W

Cryocooler Stage 2
Radiation: 0.1W
Conduction w/ TT: 1.32W
Current Leads: 0.2W
Total: 1.62W

Lumped Parameter model and heat loads for another example design
Superconductor stability

Conductor Characterization at OSU (Sumption) and AFRL (Haugan)

- Conductor $J_c$ vs $B$ for a given conductor type
- Field Ramping stability measurements
- RRR for selected strands
- SEM for a given strand type
- AC losses
Other applications: Offshore Wind

Weight of GE 10MW LTS generator = 93 mt
Further weight reduction possible with completely air core design with higher fields

Offshore wind costs

Large deviation across different wind sites, turbine architecture, OEM, etc., but overall costs need to reduced significantly
LCOE Comparisons

Drivetrain Capex

LTSC Generator allows Increasing rating to 10MW and drivetrain cost ($/kW) reduction by 30% over PMDD*, 38% over Geared, 28% over HTSCG

Cost of Energy

• Baseline is 5MW-126m
• Proposed LTSC Gen is 10MW-160m
• COE Reduction
  • 13% reduction from PMDD, with potential to reduce SC wire cost further
  • 18% reduction over geared

* Based on 2010 Maples et al. (NREL/TP-5000-49086), which assumes 2010 rare-earth material prices

Discussion