Attempting to Shift a Paradigm: HTS Generators for Cost-Sensitive Applications

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Osnabrück, 2016-04-20
Superconductors are Smart Materials to Work With

- High current density
  - $100 \times$ that of copper

- Low Ohmic dissipation
  - $100 \text{ mV}$ rotor voltage

- Low thermal losses
  - $100 \text{ W}$ at cryogenic temperatures
  - $10 \text{ kW}$ at room temperature

- Low material cost
  - $1/10$th of copper

* Round numbers
** Comparing at the same current. Like semiconductors, superconductor wire cost massively depend on manufacturing volume.
What Could Superconductors Mean for Drive Trains?

- Current mindset:
  - Geared drive trains are lightweight, cost efficient, and proven.
    Vs.
  - Direct drive has no fault-prone gearbox: It is thus preferable, and therefore it is higher Capex

- Superconductor mindset:
  - Direct drives are lightweight, cost effective and reliable.

- However, is this realistic?
Some Perceived and Real Risks of Using Superconductors (According to this Author)

- There are the “normal” risks of any technology implementation.
- On top there are specific concerns related to superconductors:

<table>
<thead>
<tr>
<th>Risk</th>
<th>Priority</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting machines will not work</td>
<td>Low</td>
<td>Many prototypes and many commercial applications prove that superconductors can be utilized</td>
</tr>
<tr>
<td>Cryogenics are too complex</td>
<td>Low</td>
<td>Cryogenics is an established industry (MRI, LNG tankers…)</td>
</tr>
<tr>
<td>Superconductivity is an unknown to the engineering people in a specific subject</td>
<td>Medium</td>
<td>In the wind industry there is no established design base existing</td>
</tr>
<tr>
<td>Superconducting wire not available at low enough cost</td>
<td>High</td>
<td>Like semiconductors the price is extremely sensitive on volume. Chicken and egg problem. Need to form supply chain alliances</td>
</tr>
</tbody>
</table>
What’s needed to enter the Market?

- What has been done:
  - Are cost of SC a show stopper?
    "No" ✔
  - Does the technology work?
    "Superconductors in rotary machines" ✔
  - What does the market need?
    "Lower cost" ✔

- What needs to be done
  - Proof in real environment
    "Build a generator and run it on a turbine"  
  - Design for low cost
    "Open potential for best cost / performance ratio"
  - Optimize Suppliers
    "Chose suppliers with low cost background"
  - Synchronize Suppliers
    "Plan a roll out scenario"
Are cost of Superconductors a Show Stopper?
Cost of Raw Materials of several Superconductors are almost identical (~1mm²) – 2G, MgB₂ und NbTi*

* vgl.: Vortrag ZIEHL III Tagung Dr. J. Müller (2012), „Supraleitende Generatoren in der Nutzung regenerativer Energiequellen“
Which market could be addressed by Superconductors?

- Extensive Analysis of *Bills-of-Material based on cost from manufacturers show:*
  - Commercialization of superconducting generators is possible in phases

```
Prototype
TAM
SC wire  <100 € / kAm
Cryocooler  <70 € / kg
Vacuum Steelworks  <22 € / kg

<8%*  
EE DD
<25 € / kAm
<25 € / kg
<10 € / kg

<20%*  
EE & PM DD
<15 € / kAm
<21 € / kg
<8 € / kg

~100%*  
EE & PM DD
DFIG & Gear Box
<4 € / kAm
<18 € / kg
<6 € / kg

* Source: JRC wind status report 2012, Roberto Lacal Arántegui et. al.
```
Review of Activities in Superconducting Generators

- Focus mostly on European activities and sort by ambition
  - **Hydrogenie (Converteam/GE )**
    - 2 MW fully tested, 8MW, 10 MW planned
  - **Innwind 10…20 MW DD (Siemens)**
    - Components demonstrated, CoE comparison @ EWEA
    - Comparing HTS to PM and to pseudo DD
  - **SeaTitan 10 MW DD (AMSC)**
    - Design complete, hardware de-risking complete
  - **Suprapower, 10 MW DD (Tecnalia, Ingeteam)**
    - Design complete, hardware in progress
  - Trend is a bit towards lower power rating (as price of superconductors comes down).
    - **EcoSwing, 3.6 MW DD (Envision)**
      - Plans to be first on a turbine
    - **Windspeed. 3.5 MW DD (ECO 5)**
      - Design basics published
Hydrogenie, First Superconductor Hydro Generator

- Partners: Converteam, E.On
  - Technology platform
  - 1789 kVA, 1700 kW, 5250 V, 28 poles, 0.95 pf, 214 rpm

- The generator tested successfully and exceeded expectations
  - Tested to 2500 kVA under nominal and under short-circuit load.
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10 MW HTC SC direct drive

**Component** | **Material** | **Cost (€)**
--- | --- | ---
**Generator** | Stator iron | 58188
| Rotor iron | 53735
| Copper | 117480
| SC | 534896 | **Total** | 764299* |
**Converter** | Switches | 160314
| Generator filter | 58084
| DC Link | 152000**
| Grid filter | 89000**
| Cooling system | 143000**
| Mechanical support | 184000** | **Total** | 786398 |
**Total drive train** | Total | 1550697

* Without cooling system cost.
**Deliverable 3.3.2 - Converter designs based on new components and modular multilevel topologies.**
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SeaTitan™ Specifications

Turbine:
- Offshore rated
- 10 MW at 10 rpm
- 190 m rotor
- 130 m tower

Generator
- Direct drive, HTS
- Medium voltage stator
- Low noise
- MTBS 12 months
- >25 year life
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SUPRAPOWER project summary: Progress as of April 2016

10 MW machine designed:
8.1 rpm, 10.1 m airgap, 48 poles

Scale machined under construction:
2 SC coils and cryostats at 10 MW scale

SC coils designed and tested
Monitoring and quench detection system
Cryostats designed. First module constructed and tested
How to go further.....
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Markets with large numbers

Cost Optimized

Large Power

Lightweight

Optimized

Power

• Hydrogenie

• Innwind

• SeaTitan

• Suprapower

• EcoSwing

• Windspeed

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Windspeed: Design

- We developed a pre-design study including benchmarking
- The complete report will be available under Creative Commons license
- Purpose is to enhance awareness about designing with superconductors

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<tr>
<td><strong>Main</strong></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>13 rpm</td>
</tr>
<tr>
<td>Rated power at terminals</td>
<td>3.69 MW (Turbine: 3.6 MW)</td>
</tr>
<tr>
<td>Rated torque</td>
<td>2.88 MNm</td>
</tr>
<tr>
<td>Pole pairs</td>
<td>32</td>
</tr>
<tr>
<td>Power converter</td>
<td>Full conversion</td>
</tr>
<tr>
<td><strong>Dimension</strong></td>
<td></td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>5500 mm</td>
</tr>
<tr>
<td>Stator active length</td>
<td>710 mm</td>
</tr>
<tr>
<td>Free mechanical airgap</td>
<td>13 mm</td>
</tr>
<tr>
<td><strong>Rotor concept</strong></td>
<td></td>
</tr>
<tr>
<td>Excitation</td>
<td>MgB$_2$ coils</td>
</tr>
<tr>
<td>Rotor back iron</td>
<td>At cryogenic temperature</td>
</tr>
<tr>
<td>Vacuum</td>
<td>Single space</td>
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Windspeed: Wire cost at point of operation

- Already today we are at the verge of competitiveness 15€ / kAm
What was considered?

- **Cost basis:**
  - Material purchased on basis of mass manufacturing
  - Assembly Labour
  - "New" material and components based on expected prices for mass manufacturing
  - Overhead, risk & margin for mass manufacturing used for benchmarking

Wire cost in mass market achievable in <3 years
Windspeed: Cost Benchmarking to Conventional Drives
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Superconductivity has matured sufficiently that we can follow an ambitious plan:

- Design, develop and manufacture a full scale multi-megawatt direct-drive superconducting wind generator

- Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark (3.6 MW, 14 rpm, 128 m rotor)

- Prove that a superconducting drive train is cost-competitive.

"EcoSwing has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 656024." “Herein we reflect only the author’s view. The Commission is not responsible for any use that may be made of the information it contains.”
Platform for Technology Validation

- The idea is to replace a PM generator with a superconducting generator
- This includes power conversion and refrigeration equipment.

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Key Project Figures

- Program: EU Horizon 2020
- Reference: 656024
- Start Date: 2015-03-01
- End Date: 2019-03-01
- Total Cost: EUR 13,846,594
- EU Contribution: EUR 10,591,734

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Consortium

- Consortium of 9 institutions
- Well defined responsibilities
- Substantial development team
Conclusion

- Superconductive generators could become technically and financially interesting
  - Significant development effort Europe-wide (and world-wide, too)
  - MgB2 – cost would allow to address DD market in 3 MW class in less than 5 years
  - 2G conductors allow even larger market access in 2020+

- Watch out for the first prototype to be installed.
ECO 5: Engineering for High-Efficient Businesses