Advantages and Challenges in high-field Rotating Machinery

MT26 Special session “Magnet Technology and Conductor for future High-Field Applications”

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Acknowledgement

- Martin Boll, Lars Kühn, Matthias Corduan, Siemens EAircraft
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- Markus Bauer, Theva
- Thomas Hildinger, Voith Hydro
Which Application?

There are many rotating machines that differ very much in torque, power and speed.
Which Application?

Share of **motor** energy use by type of end-use in the **industrial sector**

- Other motors: 36%
- Pumps: 22%
- Fans: 18%
- Air compressors: 7%
- Conveyors: 2%


Each application and each market has specific requirements and different users.
Market Perspective for Rotating Machines


**New deliveries 2018-2037**

*Source: Ascend, Airbus*

*Note: 100+ seaters (passenger aircraft)*

*Categories: Demand forecast is based on generic neutral seating categories grouped into the following segments for simplification purpose*

<table>
<thead>
<tr>
<th>Pax Units</th>
<th>Africa</th>
<th>Asia-Pacific</th>
<th>CIS</th>
<th>Europe</th>
<th>Latin America</th>
<th>Middle East</th>
<th>North America</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Small</td>
<td>843</td>
<td>12494</td>
<td>998</td>
<td>5512</td>
<td>2425</td>
<td>1214</td>
<td>5066</td>
<td>28552</td>
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<tr>
<td>Medium</td>
<td>204</td>
<td>2204</td>
<td>140</td>
<td>1042</td>
<td>210</td>
<td>533</td>
<td>679</td>
<td>5012</td>
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<tr>
<td>Large</td>
<td>50</td>
<td>565</td>
<td>39</td>
<td>315</td>
<td>55</td>
<td>466</td>
<td>150</td>
<td>1640</td>
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<tr>
<td>X-Large</td>
<td>34</td>
<td>380</td>
<td>44</td>
<td>203</td>
<td>17</td>
<td>612</td>
<td>69</td>
<td>1359</td>
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<tr>
<td>Total</td>
<td>1131</td>
<td>15643</td>
<td>1221</td>
<td>7072</td>
<td>2707</td>
<td>2825</td>
<td>5964</td>
<td>36563</td>
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</table>

<table>
<thead>
<tr>
<th>Pax Values ($US billion)</th>
<th>Africa</th>
<th>Asia-Pacific</th>
<th>CIS</th>
<th>Europe</th>
<th>Latin America</th>
<th>Middle East</th>
<th>North America</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>88</td>
<td>1424</td>
<td>107</td>
<td>618</td>
<td>265</td>
<td>133</td>
<td>539</td>
<td>3174</td>
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<tr>
<td>Medium</td>
<td>55</td>
<td>585</td>
<td>37</td>
<td>276</td>
<td>56</td>
<td>144</td>
<td>181</td>
<td>1334</td>
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<tr>
<td>Large</td>
<td>17</td>
<td>192</td>
<td>13</td>
<td>107</td>
<td>19</td>
<td>159</td>
<td>51</td>
<td>558</td>
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<tr>
<td>X-Large</td>
<td>13</td>
<td>147</td>
<td>18</td>
<td>80</td>
<td>6</td>
<td>246</td>
<td>27</td>
<td>537</td>
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<tr>
<td>Total</td>
<td>173</td>
<td>2348</td>
<td>175</td>
<td>1081</td>
<td>346</td>
<td>682</td>
<td>798</td>
<td>5603</td>
</tr>
</tbody>
</table>

There is a huge market perspective (e.g. 70 billion USD in 2030 for offshore wind)
Which Type?

- Synchronous machine
  - Fully superconducting
    - Electrical excitation
    - Permanent magnets
  - Rotor superconducting
    - Electrical excitation
    - Permanent magnets
- Asynchronous machine
- DC machine
- Reluctance machine
- Homopolar motor
- Transversal flux machine
- Linear drives
- and some more

Different choices, but always: B-field $\perp$ current $\perp$ motion

Picture: Courtesy T. Arndt
**State of the Art of HTS rotating machines**

- Machines with a rating of up to 36 MVA were built and tested

<table>
<thead>
<tr>
<th>Manufacturer / Country</th>
<th>Machine</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMSC (US)</td>
<td>5 MW demo-motor</td>
<td>2004</td>
</tr>
<tr>
<td></td>
<td>8 MVA, 12 MVA synchronous condenser</td>
<td>2005/2006 <em>(Field test)</em></td>
</tr>
<tr>
<td></td>
<td>36 MW ship propulsion motor</td>
<td>2008</td>
</tr>
<tr>
<td>GE (US)</td>
<td>5 MVA homopolar induction motor</td>
<td>2008</td>
</tr>
<tr>
<td>LEI (US)</td>
<td>5 MVA high speed generator</td>
<td>2006</td>
</tr>
<tr>
<td>Kawasaki (JP)</td>
<td>1 MW ship propulsion</td>
<td>200?</td>
</tr>
<tr>
<td>IHI Marine, SEI (JP)</td>
<td>2.5MW ship propulsion motor</td>
<td>2010</td>
</tr>
<tr>
<td>Doosan, KERI (Korea)</td>
<td>1 MVA demo-generator</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>5 MW motor ship propulsion</td>
<td>2011</td>
</tr>
<tr>
<td>Siemens (Germany)</td>
<td>4 MVA industrial generator</td>
<td>2008 <em>(Field test)</em></td>
</tr>
<tr>
<td></td>
<td>4 MW ship propulsion motor</td>
<td>2010</td>
</tr>
<tr>
<td>Converteam (UK)</td>
<td>1.25 MVA hydro-generator</td>
<td>2010</td>
</tr>
<tr>
<td>Ecoswing (EU)</td>
<td>3 MW wind generator</td>
<td>2018 <em>(Field test)</em></td>
</tr>
</tbody>
</table>

So far three field test of more than a MW superconducting machines were reported

MT26 Special Session, M. Noe “Advantages and challenges in high-field rotating machinery”
What is important for rotating machinery

- Example: Conventional synchronous machine with electrical excitation

3 phase stator winding

Air gap

Characeristic
- Stator winding in iron grooves
- Backiron to confine flux to machine and close magnetic circuit
- Copper windings
- Iron in rotor and stator
- Small air gap
What is important for rotating machinery

- Example: Conventional synchronous machine with electrical excitation

A high magnetic field enables a considerable increase in all important machine parameters.
Limitations

- **Length**
  - Oscillations, mechanical stability, bending → varying airgap, stress cycles

- **Diameter**
  - Transport, circumferential speed, maximum available forgings

- **Current Density**
  - Losses, heating

- **Magnetic Field**
  - Saturation of iron, ferromagnetic behaviour

- **Speed**
  - Depends on application, maximum forces

- **Plus many other constraints**
  - User benefit
  - Cost pressure
  - Robust and reliable
Limitations Onshore Wind Generators

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Platform</th>
<th>Capacity</th>
<th>Rotor diameter</th>
<th>Max hub height</th>
<th>Drivetrain</th>
<th>Specific power rating</th>
<th>Current status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enercon</td>
<td>EP5</td>
<td>Up to 5MW</td>
<td>147m, 160m</td>
<td>166m</td>
<td>Direct drive</td>
<td>294W/m2 (E147)</td>
<td>Prototype imminent</td>
</tr>
<tr>
<td>GE</td>
<td>Cypress</td>
<td>5.3MW</td>
<td>158m</td>
<td>161m</td>
<td>HSG</td>
<td>270W/m2</td>
<td>Prototype installed late 2018</td>
</tr>
<tr>
<td>Nordex</td>
<td>Delta4000</td>
<td>Up to 5MW</td>
<td>149m, 155m</td>
<td>164m</td>
<td>HSG</td>
<td>239W/m2 (N155/4.5)</td>
<td>In series production</td>
</tr>
<tr>
<td>Siemens Gamesa</td>
<td>5.X</td>
<td>5.8MW</td>
<td>155m, 170m</td>
<td>165m</td>
<td>HSG</td>
<td>256W/m2 (SG-155)</td>
<td>Prototype expected mid-2020</td>
</tr>
<tr>
<td>Vestas</td>
<td>EnVentus</td>
<td>5.6MW</td>
<td>150m, 162m</td>
<td>166m</td>
<td>MSG</td>
<td>272W/m2 (V162)</td>
<td>Prototype imminent</td>
</tr>
</tbody>
</table>

Source: Windpower Monthly

Hot Topics
- Two piece blades to overcome transport and logistical challenge
- New installation technology and techniques to speed up process of hoisting
Limitations Large Hydro Generators

Hydro Generators - Generator Technology Index

- Energy Density of generators increased by 50% since the fifties!
  → development over 5 decades

- New Silicon Steel Grades
  → low grades GNO (M270, M250, M230, ...)

- Vacuum Pressure Impregnation Insulation
  → from Polyester to Epoxy
  → from Mica-Split to Mica-Paper
  → process control improvements
  → automatic taping machines
  → reduced thickness of ground wall

- New Calculation Methods and Design Tools
  → FEM, CFD, CAD, ....

Present limitations: $B \leq 1.3 \, T$, $A_1 < 100 \, A/mm$, diameter < 20 m, length < 4 m

Data from Thomas Hildinger, Voith Hydro

MT26 Special Session, M. Noe “Advantages and challenges in high-field rotating machinery”
What are the Implications of HTS?

Example: Synchronous Machine with electrical excitation

Characteristic of HTS winding in rotor for higher magnetic fields
- Air gap normal conducting stator winding
- Rotorwinding with HTS
- No iron in motor
- Cryostat acts as damper winding

As a result
- Larger air gap
- Smaller synchronous reactance
- Different excitation system
What are the Implications of HTS?

**Example Wind Generator**

- 3.6 MW | 14 rpm
- 4 m
- 65 tons
- $B_{\text{max air gap}} = 1.65 \, \text{T}$

**Example Generator for E-Aircraft Study**

- 10 MW | 7000 rpm | 21 kW/kg | > 98 %, 476 kg
- $B = 1.11 \, \text{T}$
- $B_{\text{max HTS}} \sim 3 \, \text{T}$

Data and picture: M. Bauer Results and lessons learned from the 3 MW EcoSwing wind power generator, EUCAS 2019, Glasgow

Data and picture: L. Kühn, et.al. High Power Density 10 MW HTS-Generator for eAircraft, EUCAS 2019, Glasgow

What is the reason for the chosen magnetic field?
Implications of High Magnetic Field for a Wind Generator

- Example: Synchronous machine with electrical excitation

- Design Option 1: Warm iron, limited magnetic field
  - Smallest air gap, smallest amount of HTS tape, a cryostat around each coil

- Design Option 2: Cold iron, limited magnetic field
  - Cryostat enlarges air gap, more HTS tapes to reach same magnetic field
  - Ecoswing used 20 km of 12 mm wide tapes

- Design Option 3: no iron, high magnetic field
  - Large air gap, considerable amount of HTS tapes to reach magnetic field

Picture: M. Bauer, “Results and lessons learned from the 3 MW EcoSwingwind power generator” EUCAS 2019, Glasgow
Implications of High Magnetic Field for an Aircraft Generator

10 MW | 7000 rpm | 21 kW/kg | > 98 %, 476 kg

Mechanical loads
- Strain from sleeve to stress carrier
- Thermal contraction
- High centrifugal load
- Torque transmission from 20 K to RT

Rotation 7000 rpm
Max. circumferential speed 133 m/s
Results in force of 9000 g

The rotor design balances superconducting limits with mechanical stress limits

Data and picture: L. Kühn, et.al. High Power Density 10 MW HTS-Generator for eAircraft, EUCAS 2019, Glasgow
Open Questions for Discussion

- Can we imagine a rotating machine with much more than 5 T?
- Is a HTS bulk material with high magnetic fields the better option than 2G HTS?
- In which application can we exploit best the high magnetic field?
- What will be the first commercial HTS application for rotating machines?
- …?

Many thanks for your attention!