Evaluation and Mitigation of AC Losses in a Fully Superconducting Machine for Offshore Wind Turbines

B. Thanatheepan, Noah Salk, Dongsu Lee
Prof. Kiruba.S.Haran

Electrical and Computer Engineering
University of Illinois, Urbana-Champaign
Advantage of Fully Superconducting Turbines

<table>
<thead>
<tr>
<th>Coper wound with gear box</th>
<th>Permanent Magnet</th>
<th>Partially superconducting</th>
<th>Fully superconducting with iron yoke/shield</th>
<th>Actively Shield Design (Preliminary design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>500 Tons</td>
<td>320 Tons</td>
<td>&gt;150 tons</td>
<td>&lt;150 tons</td>
</tr>
</tbody>
</table>

- Direct drive and larger capacity 10MW to 20MW
- Increased efficiency up to 99%.
- Weight 30-50% less than a permanent magnet machine.
- 10-20% reduction in capital cost.
- Reduction in maintenance cost
- Efficient energy capturing capability at partial loads.


Proposed Machine Specification – Active Shield

• Active magnetic shield to contain the flux within the machine
• No core loss or core saturation - explore peak fields up to 10T ??
• Further weight reduction – explore low pole count designs
  • Estimated low ac loss ??

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>10MW</td>
</tr>
<tr>
<td>Speed</td>
<td>10 rpm</td>
</tr>
<tr>
<td>Weight</td>
<td>Less than 50 Ton</td>
</tr>
<tr>
<td>Ac loss</td>
<td>Less than 1 kW</td>
</tr>
<tr>
<td>Pole number</td>
<td>10 / 20 /30 / 40/50/60</td>
</tr>
<tr>
<td>Superconductor</td>
<td>MgB$_2$</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>20 K</td>
</tr>
<tr>
<td>Armature Current density</td>
<td>Max 200 A$_{rms}$/mm$^2$</td>
</tr>
<tr>
<td>Field current density</td>
<td>200 A/mm$^2$</td>
</tr>
<tr>
<td>Shield current density</td>
<td>200 A/mm$^2$</td>
</tr>
</tbody>
</table>
Low ac loss MgB$_2$ superconductors (HyperTech)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conductor I 0.32/10/5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_c$</td>
<td>Critical current density at 0.4 self-field at 20K [A/m$^2$]</td>
<td>6.6e9</td>
</tr>
<tr>
<td>$D_0$</td>
<td>SC diameter [mm]</td>
<td>0.32</td>
</tr>
<tr>
<td>$d_f$</td>
<td>Filament diameter [$\mu$m]</td>
<td>10</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of filaments</td>
<td>114</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>The area fraction of the wire that is SC</td>
<td>0.15</td>
</tr>
<tr>
<td>$\lambda_{eff}$</td>
<td>Effective fill factor</td>
<td>0.49</td>
</tr>
<tr>
<td>$\rho_{eff}$</td>
<td>Effective transverse resistivity [Ω-m]</td>
<td>12.5e-8</td>
</tr>
<tr>
<td>$L$</td>
<td>The twist pitch (mm)</td>
<td>5</td>
</tr>
</tbody>
</table>
Flux density Vs Critical Current Density

Measured B Vs Jc for MgB2 conductors at 20 K

\[ J_E = \lambda \times \pi \times \frac{D^2}{4} \times J_C \]

At 20K and 2T field density \( J_E = 200A/mm^2 \) at 20K and 3T \( J_E = 113A/mm^2 \)

Operating current – Safety margin \( I_A = 0.50 \times I_c \), \( I_F = 0.70 \times I_c \)
AC Losses – Carr’s Model

- Penetration field
  \[ B_p = 0.4 \times \mu_0 \times J_c \times d_f \]

- Hysteresis loss
  \[ P_h = \left( \frac{4}{3} \right) \times B_m \times J_c \times d_f \times f \]

- Eddy current loss
  \[ P_e = \left( \frac{\pi^2}{K \times \rho_{\text{eff}}} \right) \times (B_m \times D_0 \times f)^2 \]

- Coupling loss
  \[ P_c = \left( \frac{1}{n \times \rho_{\text{eff}}} \right) \times (f \times L_p \times B_m)^2 \]

- Transport current loss
  \[ P_I = \left( \mu_0 \times \frac{f}{\pi} \right) \times (Ic^2) \times \left( 1 - \frac{I_0}{I_c} \right) \times \log \left( 1 - \frac{I_0}{I_c} \right) + \left( \frac{I_0}{I_c} \right)^2 - 0.5 \times \left( \frac{I_0}{I_c} \right)^2 \]

  \[ \pi \times \left( \frac{D_0}{2} \right)^2 \]

- K=4, n=2 constants

\[ J_c \] Critical current density [A/m²]
\[ D_0 \] SC diameter [mm]
\[ d_f \] Filament diameter [μm]
\[ n \] Number of filaments
\[ \lambda \] The area fraction of the wire that is SC
\[ \rho_{\text{eff}} \] Effective fill factor
\[ \rho_{\text{eff}} \] Effective transverse resistivity [Ω·m]
\[ L \] The twist pitch (mm)

- Develop conductors with low losses
- Design machine to minimize losses
  - Reduce operating frequency – low pole count
    - weight
  - Reduce operating field
    - size
  - Optimize between electrical and magnetic loading
  - Optimize between volume and w/cm³ losses

### Optimization

**Parameter** | **min** | **max**
---|---|---
Armature slot inner radius [X1](mm) | 1500 | 2000
Armature slot radial height [X2](mm) | 1 | 100
Radial distance between field coils and shield coils [X3] (mm) | 1 | 100
Field slot radial height [X4] (mm) | 1 | 100
Field slot circumferential width [X5] (Angle Degree) | 0.2 | \( f(pole) \)
Shield slot radial height [X6](mm) | 1 | 100
Shield slot circumferential width [X7](mm) | 1 | \( f(pole) \)
Radial distance between shield coil and iron shield [X9] (mm) | 1 | 100
Radial iron shield height [X8] (mm) | 1 | 100
Armature current density [X10] (A/mm2) | 50 | 200

\[
X = [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}]
\]

- Magnetic loading
- Electrical loading

\[
X_{optimal} = \text{Minimize}(\text{Weight, ac loss})_X
\]
Optimization

Optimization algorithms (Genetic Algorithms)

Design variables
\[ X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10} \]

Armature

Field

Shield \_sc

Shield \_stec

Torque based on FEA
\[ T^e = \frac{3}{2} p \lambda_d i_q \]

Axial length for rated torque
\[ l_a = \frac{\text{rated } T^e}{T^e} \]

Check critical current density margin

Out-side flux [50mT at Path 4]

Max. radius of Machine [<2.2m]

Max. axial length [<5m]

Calculation performance [cost, weight, ac loss]

Iteration satisfaction [pop=100 gen=100]

Select Best Solution

No

Yes

No

Yes

No

Yes

Cost=high Weight=high

No

Yes

Select Best Solution

8
Optimal front - 10 Pole machine designs

All machine designs satisfying constraints

- Active shield designs reduce weight significantly
- Air-gap field density and stack length of the motor has significant tradeoff
- Different stack length designs can be chosen with corresponding change in ac loss.
• AC loss is estimated in the armature axial length as well as in the end windings.
• Only active mass is considered for the weight.
• Optimal-pareto front for 10, 20, 30 and 40 pole count designs.
• Weight and ac loss has the tradeoff

- As pole count increases weight decreases and ac losses increases
- Between optimized pole counts low pole counts looks desirable due to their low ac loss performance.
Assuming armature current density is 50% of the $J_c$ at applied field density \(0-2\text{T}\)

- 10 rpm machine with 10, 20, 30, 40, and 60 pole designs with 0T to 2T airgap flux density
- Armature SC machine conductors experience varying flux density across a slot
- Optimal design space for wind: 0.8 T to 1 T
- Optimal design space for electric propulsion: 0.8 to 1 T

Feasible design space
## Optimization Results – 10 pole

### 10 pole Machine designs – Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lowest weight</th>
<th>Lowest Ac loss</th>
<th>Optimal design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter [m]</td>
<td>4.18</td>
<td>4.34</td>
<td>4.29</td>
</tr>
<tr>
<td>Axial length [m]</td>
<td>3.34</td>
<td>4.72</td>
<td>2.45</td>
</tr>
<tr>
<td>Air-gap flux density [T]</td>
<td>0.88</td>
<td>0.86</td>
<td>0.91</td>
</tr>
<tr>
<td>Outside flux density [T]</td>
<td>0.049</td>
<td>0.048</td>
<td>0.044</td>
</tr>
<tr>
<td>Armature SC length [km]</td>
<td>2852</td>
<td>1190</td>
<td>1494</td>
</tr>
<tr>
<td>Field SC length [km]</td>
<td>3316</td>
<td>4850</td>
<td>2610</td>
</tr>
<tr>
<td>Shield SC length [km]</td>
<td>1656</td>
<td>2683</td>
<td>1544</td>
</tr>
<tr>
<td>Total SC length [km]</td>
<td>8125</td>
<td>7917</td>
<td>5648</td>
</tr>
<tr>
<td>Iron shield weight [Ton]</td>
<td>4.27</td>
<td>19.51</td>
<td>7.57</td>
</tr>
<tr>
<td>Total loss [W]</td>
<td>1135</td>
<td>477</td>
<td>618</td>
</tr>
<tr>
<td>Weight (Iron and SC) [Ton]</td>
<td>9.7</td>
<td>25.3</td>
<td>11.4</td>
</tr>
<tr>
<td>Cost (Iron and SC) [million $]</td>
<td>16.2</td>
<td>17.5</td>
<td>11.3</td>
</tr>
</tbody>
</table>

- All the designs converge towards active shield designs
- Air-gap flux density and active length affect ac losses

- High Loss = 1135 W, Low weight = 9.7 Ton
- Low ac loss = 477 W, High Weight = 25.3 Ton
Machine designs with ac losses 477W and weight 25.3 Ton could be achieved with 10-poles
Best design ac loss 618 W, weight 11.3 Ton, axial length is 2.45 m and diameter is 4.29 m.

Total system weight and efficiency considering cryogenic system

\[
\text{Required cryocooler power} \approx \frac{90}{1.5} \times 618 = 37.08\text{KW}
\]

\[
\text{efficiency} \approx \frac{1\text{MW} - 37.698\text{KW}}{1\text{MW}} \times 100 = 99.6\%
\]

\[
\text{System weight} \approx 11.3 \times 200\% + \frac{10}{1.5} \times 618 = 38\text{Ton}
\]
Conclusion and future works

- Fully superconducting machines attractive for 10 MW scale wind turbines.
- Armature winding ac losses and associated added cryogen system weight are significant challenges.
- Relatively low field, low pole-count designs preferred. AC loss data close to operating conditions needed for more rigorous analysis.
  - Machine design with ac losses less than 1KW
- Iron yoke weight dominates in passively shielded designs. Actively shielded designs give lowest weight.
  - Machine design with weight less than 50 Ton
- Mechanical design needs to be refined to estimate total weight including non-active components.
- TRL increase will be sought within ac loss measurement with race track winding build and test under rotating magnetic setup.