Investigation on Multi-Phase Armature Windings for HTS Wind Turbine Generators

Dong Liu*, Xiaowei Song*, Hongzhong Ma and Jianni Dong

1. Introduction

- Superconducting windings (partially superconducting) have induced AC losses in the HTS field winding. Usually, an electromagnetic (EM) shield is applied between the field winding and the stator.

- The mechanical air gap is also kept sufficiently large to reduce the armature reaction on the rotor parts. This large gap reduces the torque production and is therefore not cost-effective.

- Multi-phase armature windings are proposed to reduce the space harmonics content in the armature reaction. This reduces the losses in the conductive EM shield and HTS field winding.

- Thus, keeping the same affordable induced losses, the mechanical air gap length can be reduced to increase the torque production by implementing multi-phase armature windings.

- This paper evaluates the effects of multi-phase windings on the torque production enhancement by changing the mechanical air gap length while examining the induced losses.

2. HTS Generator

- This HTS generator is designed for a 10-MW, 9.6-rpm direct-drive wind turbine, with a rated torque of 11 MNm.

- The generator is optimized for a minimum levelized cost of energy of the whole wind turbine.

- The field winding is superconducting with 2G HTS wires (GdBCO) operating at 30 K. The armature winding is integral-slot distributed winding working at 120 °C.

Specifications and parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air gap diameter</td>
<td>512 mm</td>
</tr>
<tr>
<td>No. of poles</td>
<td>26</td>
</tr>
<tr>
<td>No. of slots</td>
<td>954</td>
</tr>
<tr>
<td>No. of turns per pole</td>
<td>124</td>
</tr>
<tr>
<td>Armature current density (RMS)</td>
<td>2.6 A/mm²</td>
</tr>
</tbody>
</table>

3. Multi-Phase Winding Concept

- Multi-phase windings apply more than three phases.

- In the context of this paper, the number of phases is multiples of three.

- Thus, the total winding is multiple sets of 3-phase windings.

- The number of phases is determined by the number of slots per pole per phase q.

<table>
<thead>
<tr>
<th>Winding distribution under one pole (half symmetry):</th>
</tr>
</thead>
<tbody>
<tr>
<td>q = 4: 9-phase winding (3 x 3 phases)</td>
</tr>
<tr>
<td>q = 3: 6-phase winding (2 x 3 phases)</td>
</tr>
</tbody>
</table>

Advantages:

- Certain harmonics of the winding MMF are fully eliminated, such as - the 5th and 7th orders with 6 phases and 12 phases, - the 11th and 13th orders with 12 phases; all these orders with 9 phases.

- Torque production is slightly higher than 3-phase windings.

- Multiple converters divide the rated power of each converter, fitting 10 MW or higher applications. Fault-tolerant design is also possible.

- Multiple phases make use of currently applied multi-converter power conversion systems for 6 MW or larger wind turbines, thus the cost will not go higher.

4. Effects on Torque Production

- The mechanical air gap length is decreased from 16 mm (reference gap length) to 8 mm.

- The produced electromagnetic torque with different multi-phase scheme is compared at these gap lengths.

- The eddy current loss induced in the EM shield (copper) and the cryostat wall (stainless steel) is compared with these multi-phase windings at these gap lengths.

<table>
<thead>
<tr>
<th>q = 4: 9 phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>q = 3: 6 phases</td>
</tr>
</tbody>
</table>

AC loss estimation

- Decreasing the mechanical gap from 16 mm to 9 mm with a 6- or 12-phases winding also results in much lower harmonics contents in the HTS field winding. A much lower AC loss can be achieved. This benefit is together with higher torque production.

5. Conclusion

- Multi-phase windings can reduce losses induced in the EM shield, cryostat wall and HTS field winding, due to space harmonics reduction.

- By applying multi-phase windings, the mechanical air gap can be reduced for higher torque production, keeping a similar induced loss.

- With a 6- or 12-phase winding, the gap can be decreased from 16 mm to 9 mm, and the torque increase is 7.2% and 9.1%, respectively.

- With a 9-phase winding, the gap can go to 11 mm and the torque rises by 6.2%.

- Overall, the findings show that applying multiple phase windings is a doable solution that benefits the torque density of HTS machines.

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>3 phases</th>
<th>9 phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>9</td>
<td>0.12</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Harmonic order

- The 9 phases are arranged as follows:

  - 3 phases for q = 3
  - 6 phases for q = 4
  - 9 phases for q = 5

Comparison of MMF harmonics spectra

- The mechanical air gap length is decreased from 16 mm (reference gap length) to 8 mm.

- The produced electromagnetic torque with different multi-phase scheme is compared at these gap lengths.

- The eddy current loss induced in the EM shield (copper) and the cryostat wall (stainless steel) is compared with these multi-phase windings at these gap lengths.