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

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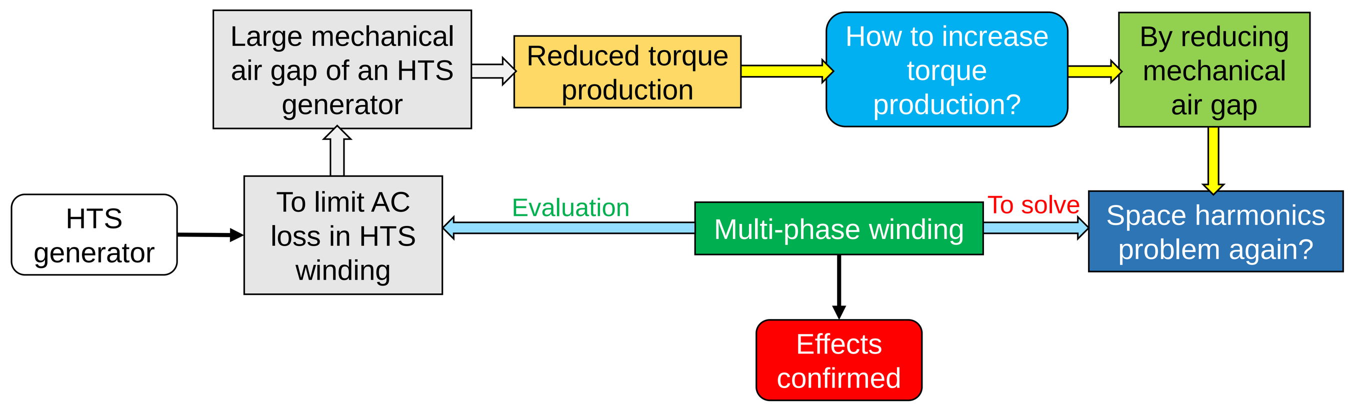
1. Introduction

- Superconducting generators (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 contents in the armature reaction -> less 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**.

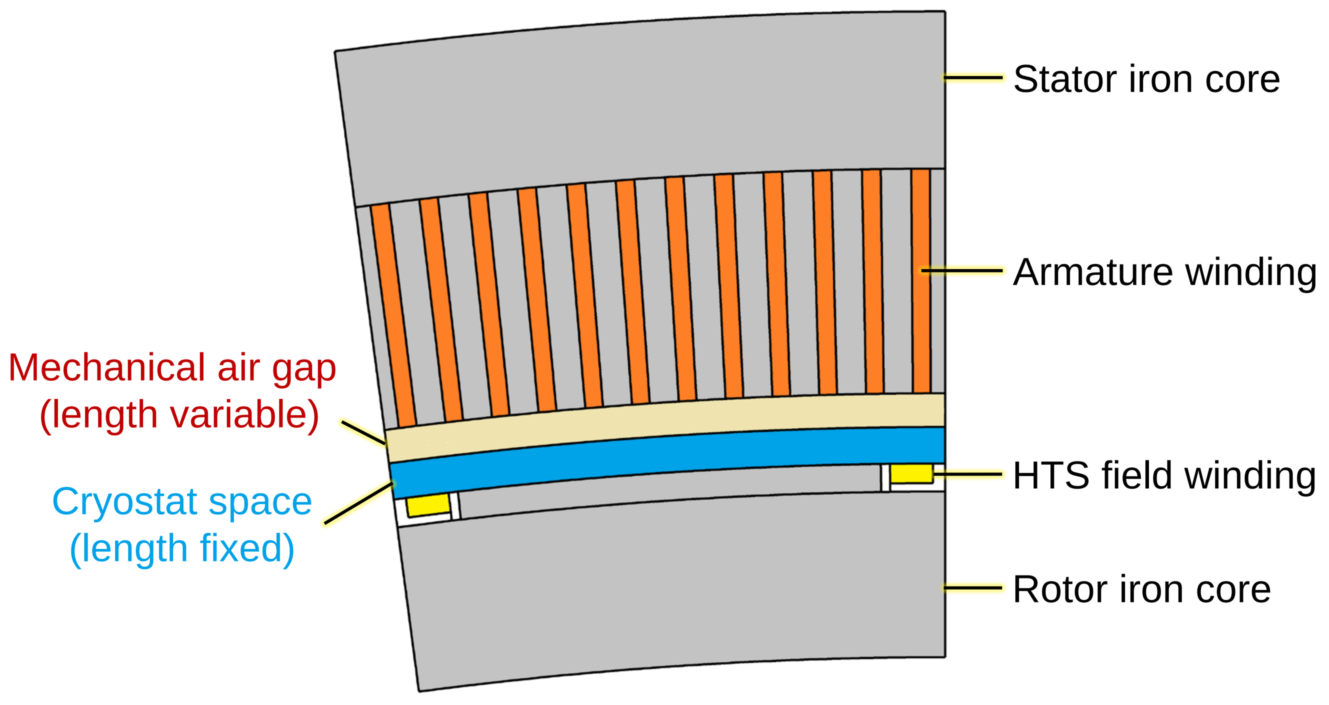


2. HTS Generator

- 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

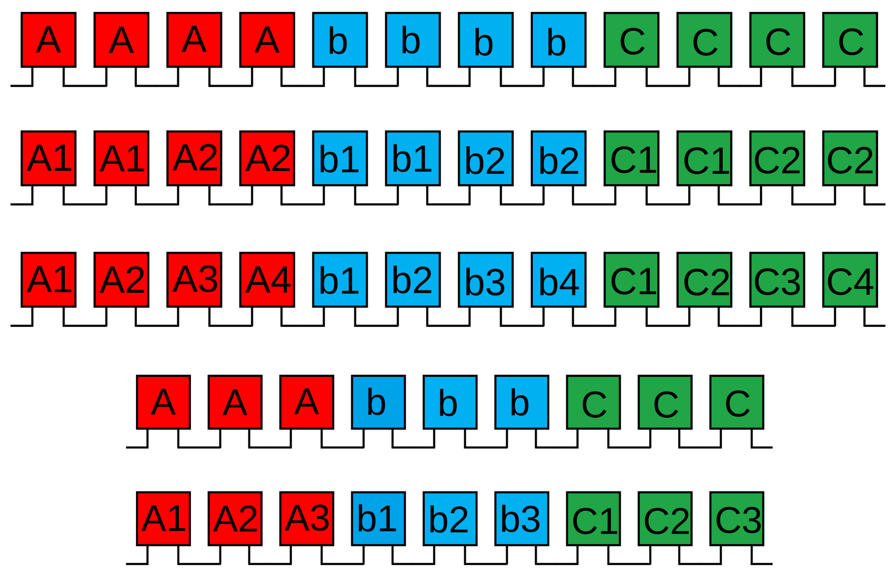
Air gap diameter	6112 mm	HTS field coil width	30.5 mm
No. of pole pairs	24	HTS field coil height	14 mm
No. of slots	576 for q = 4 432 for q = 3	Engineering field current density	120 A/mm^2
No. of turns per pole	124	Armature current density (RMS)	2.6 A/mm^2



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.

Winding distribution under one pole (half symmetry):



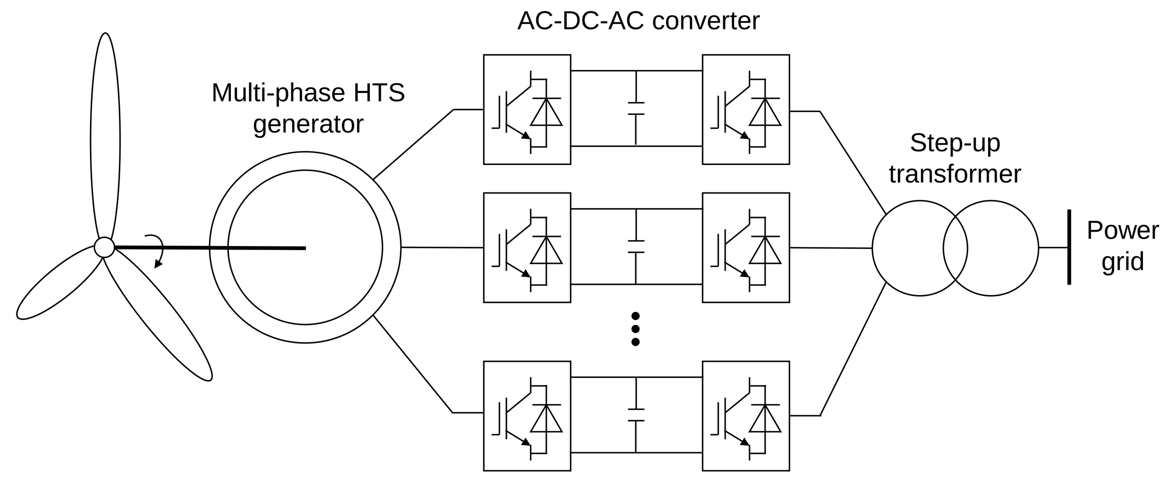
3-phase base winding (q = 4)

6-phase winding (2 x 3 phases)
Current phase shift angle: 30°

12-phase winding (4 x 3 phases)
Current phase shift angle: 15°

3-phase base winding (q = 3)

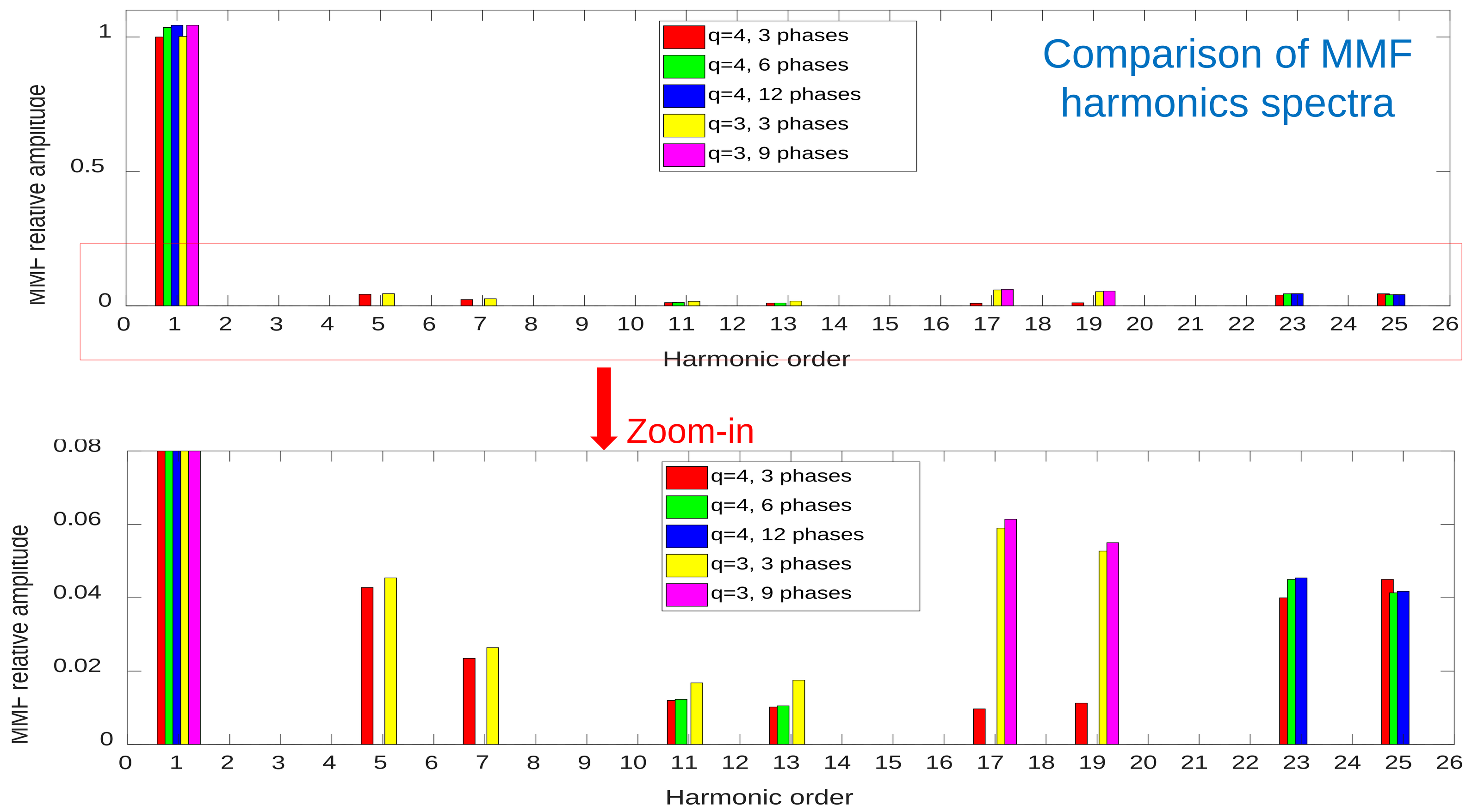
9-phase winding (3 x 3 phases)
Current phase shift angle: 20°



Implementation of a multi-phase generator to the power conversion system of a direct-drive wind turbine.

Advantages

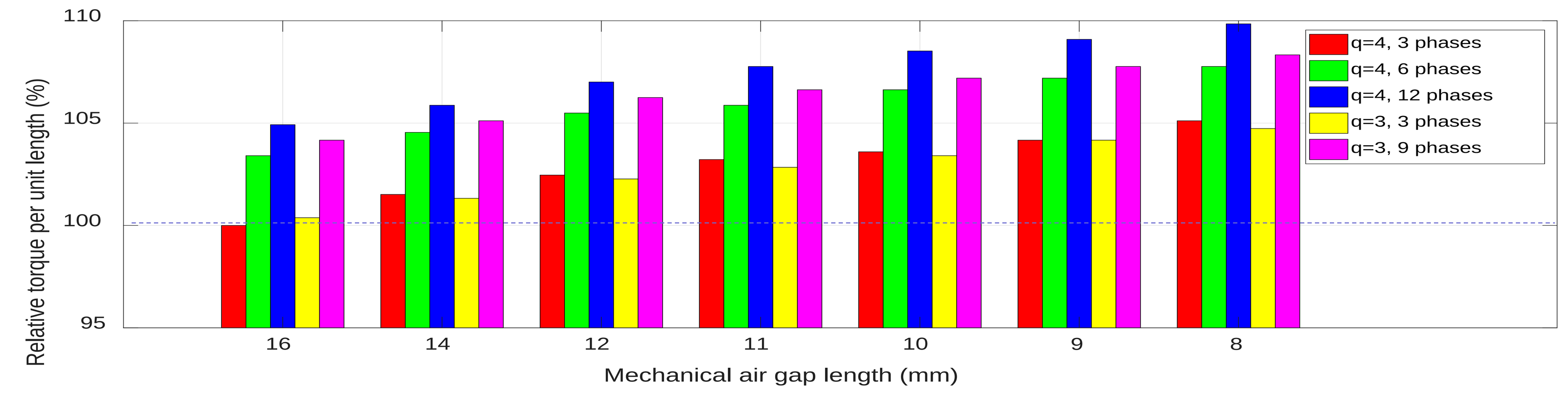
- Certain harmonics of the winding MMF are fully eliminated, such as
  - the 5th and 7th orders with 6 phases and 12 phases,
  - the 11th and 13th orders with 12 phases; all these orders with 9 phases.
- Torque production is slight higher than 3-phase windings.
- Multiple converters divide the rated power of each converter, fitting 10 MW or higher applications. Fault-tolerant design is also possible.
- Multiple phases make use of currently applied multiple-converter power conversion systems for 6 MW or larger wind turbines, thus the cost will not go higher.

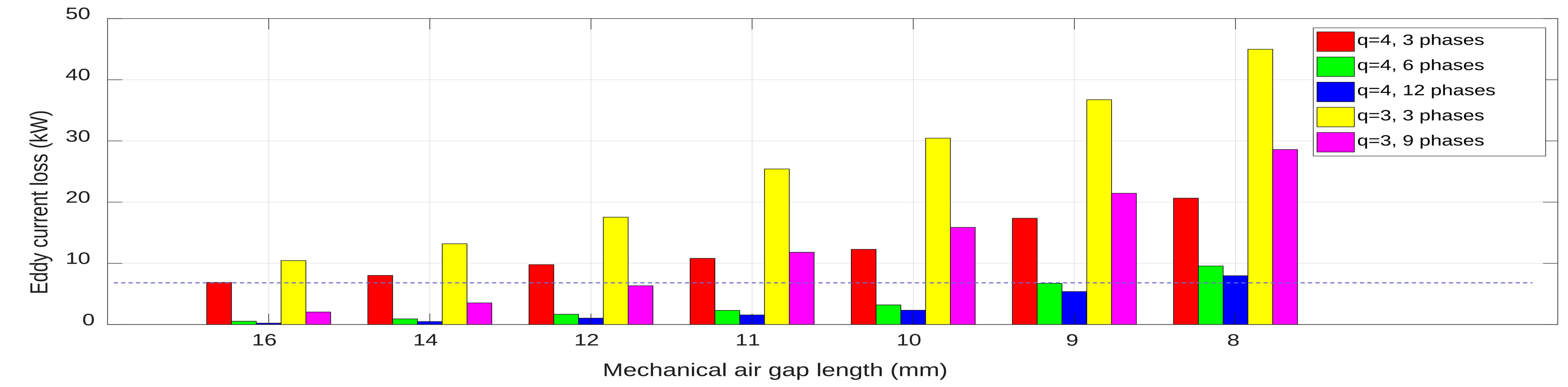


Comparison of MMF harmonics spectra

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.



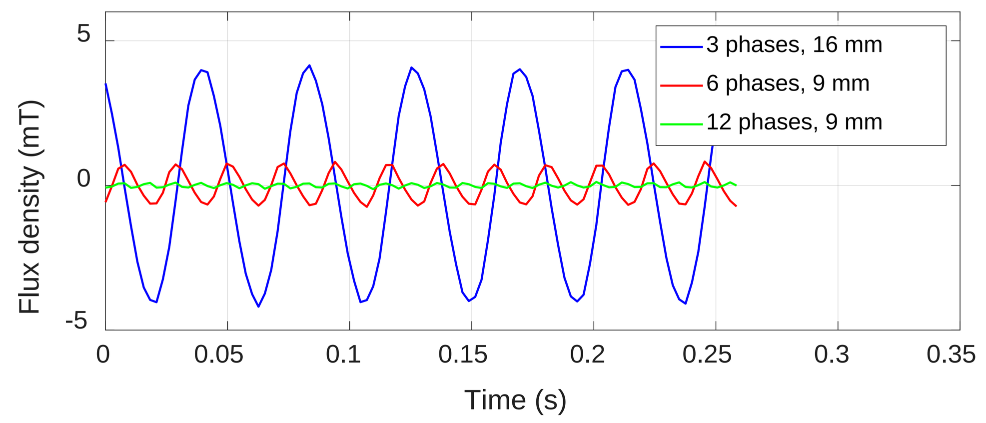


q = 4

- The gap of 9 mm using 6 phases has the same loss as the gap of 16 mm. The loss is further lower using 12 phases.
- At the gap of 9 mm, the torque is increased by 9.1% using 12 phases, and by 7.2% using 6 phases.
- The gap smaller than 9 mm, i.e. 8 mm, leads to higher losses compared with the 16-mm gap, 3-phase winding. This is due to slotting harmonics.

q = 3

- The losses are generally higher than the cases of q = 4.
- The gap length of 11 mm may be the maximum. The torque increase is 6.2% with 9 phases. Thus, q = 3 is not as good as q = 4, let alone q = 2 or 1.



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.

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