Performance of Multi-Layer Fractional-Slot Concentrated Windings for Superconducting Wind Turbine Generators under Normal and Short-Circuit Operation Conditions

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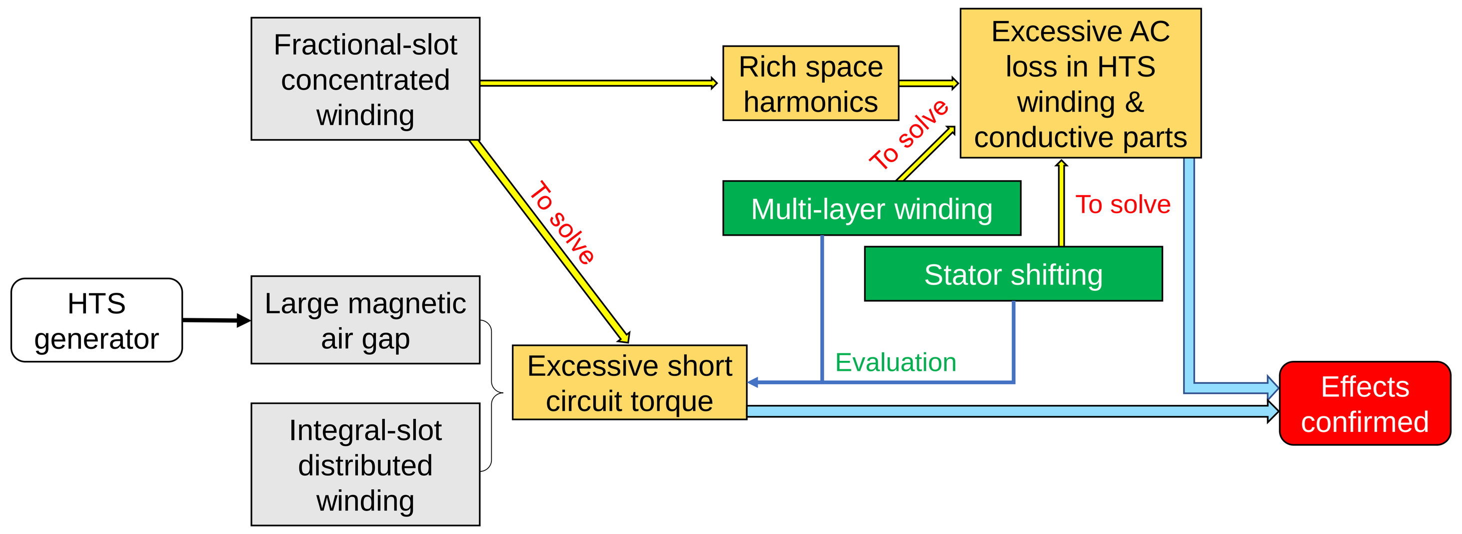
1. Introduction

- Superconducting generators (partially superconducting) have large magnetic air gaps and thus their short circuit torque can be as high as more than ten times the rated torque. This is not acceptable in wind turbine applications.
- Fractional-slot concentrated windings (FSCWs) can be used instead of integral-slot distributed windings (ISDW) for suppressing the short circuit torque under 3 times the rated torque, due to large leakage inductances.
- However, FSCWs produce rich space harmonics. These space harmonics induce excessive AC losses in the HTS field winding and unacceptably high eddy current losses in the conductive parts on the rotor side.
- This paper proposes to apply **multi-layer windings** and **stator shifting** to reduce the space harmonics from the FSCW.
- Their effects on the normal operation, i.e. torque production, induced losses in the rotor, and short circuit torque are evaluated.

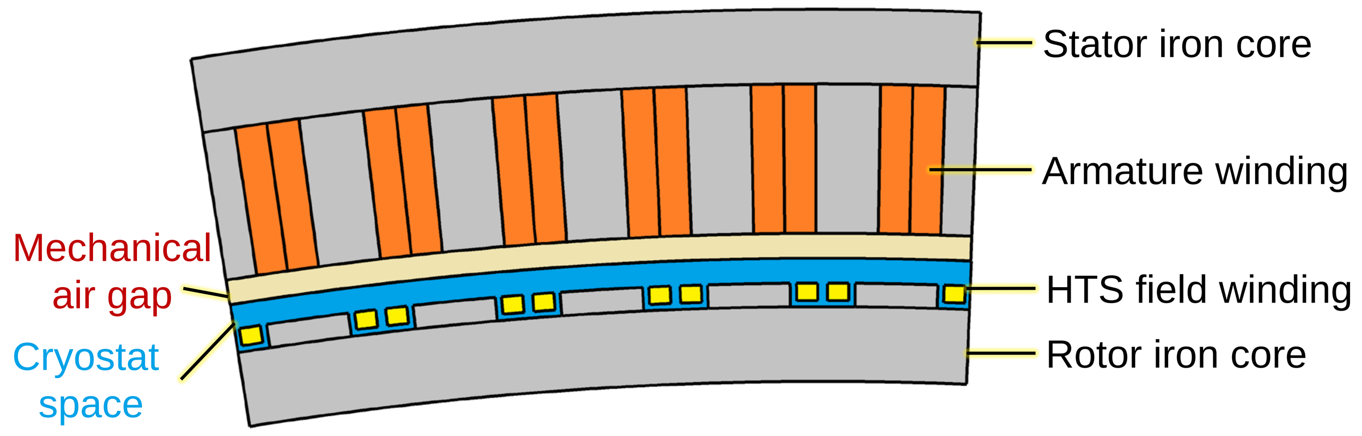


2. HTS Generator

- 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 fractional-slot concentrated winding working at 120 °C.

Specifications and parameters

Air gap diameter	6112 mm	HTS field coil width	17.1 mm
No. of pole pairs	80	HTS field coil height	14 mm
No. of slots	192 for 4L 384 for SS	Engineering field current density	122 A/mm^2
No. of turns per pole	70	Armature current density (RMS)	2.6 A/mm^2



3. Multi-Layer Winding Concept

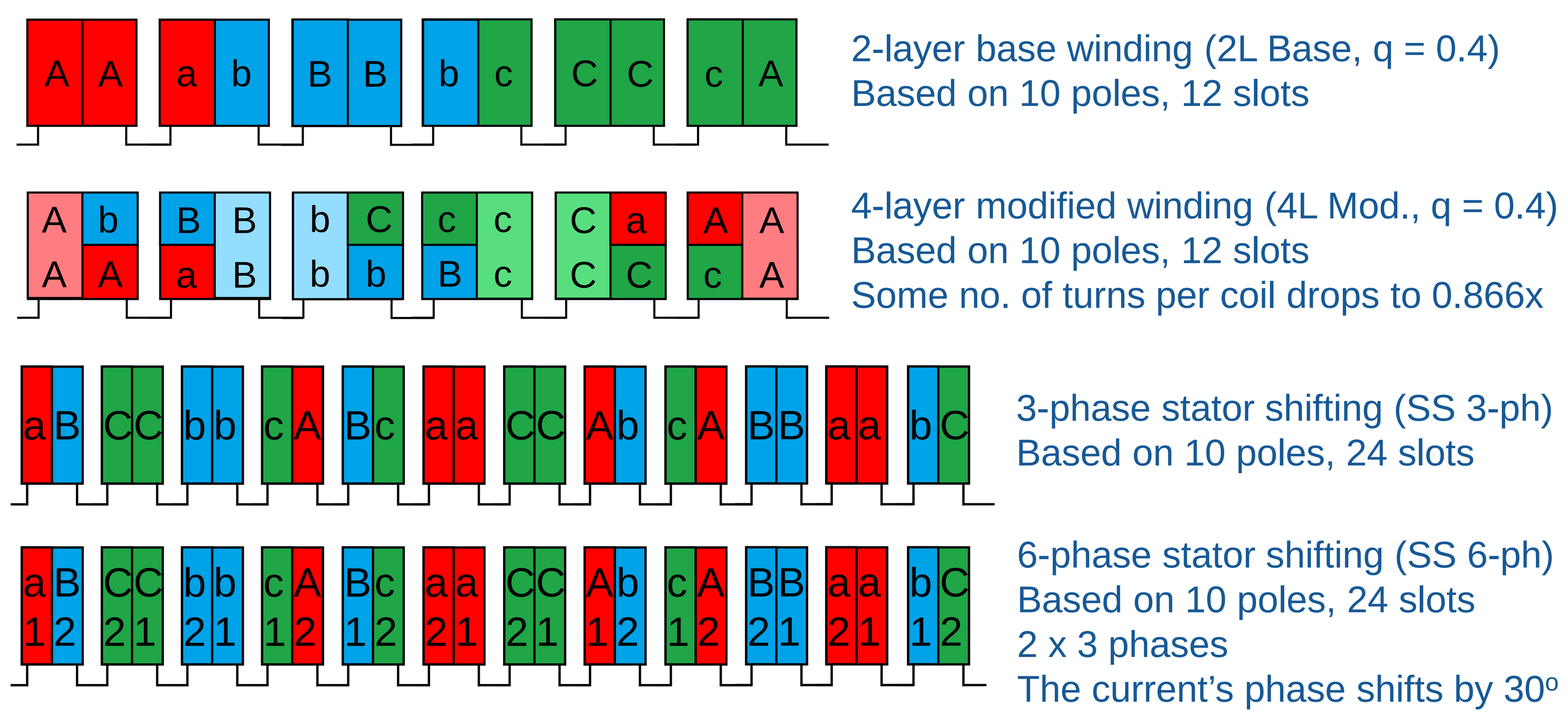
Multi-layer windings

- Multi-layer windings have 4 layers in one slot, originating from conventional 2-layer (2L) windings.
- The original 4-layer (4-L) winding has the 1st order MMF harmonic while the modified 4-layer winding does not, since the number of turns is manipulated.

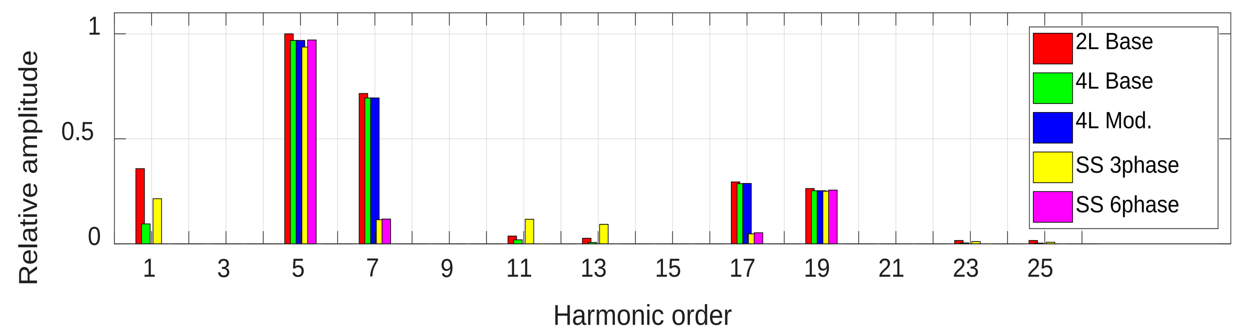
Stator shifting windings

- Stator shifting windings have two layers in one slot, also originating from conventional 2-layer windings.
- The number of slots is doubled, keeping the characteristics of windings with q = 0.4.
- Three phases windings have the 1st order MMF harmonic while six phases well eliminate this critical order.
- Six phases consist of two 3-phase windings with a current phase shift angle of 30°.

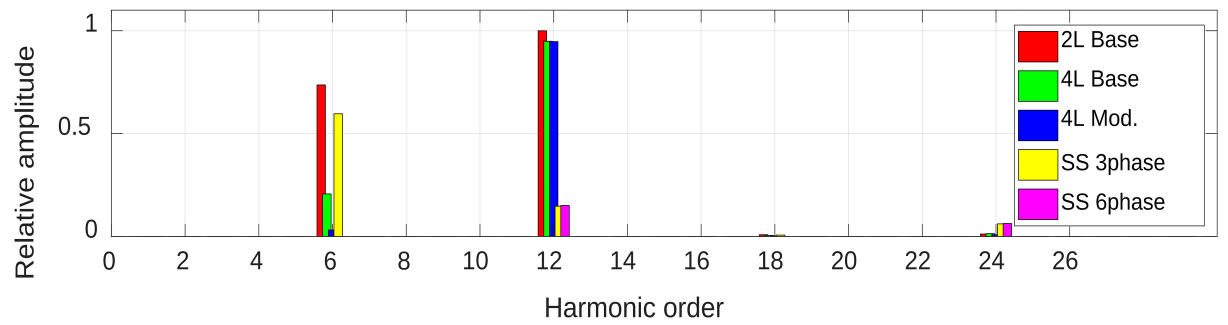
Winding distribution under 5 poles (half symmetry):



Comparison of MMF harmonics spectra



Comparison of flux density harmonics spectra in the HTS field winding



Multi-layer windings

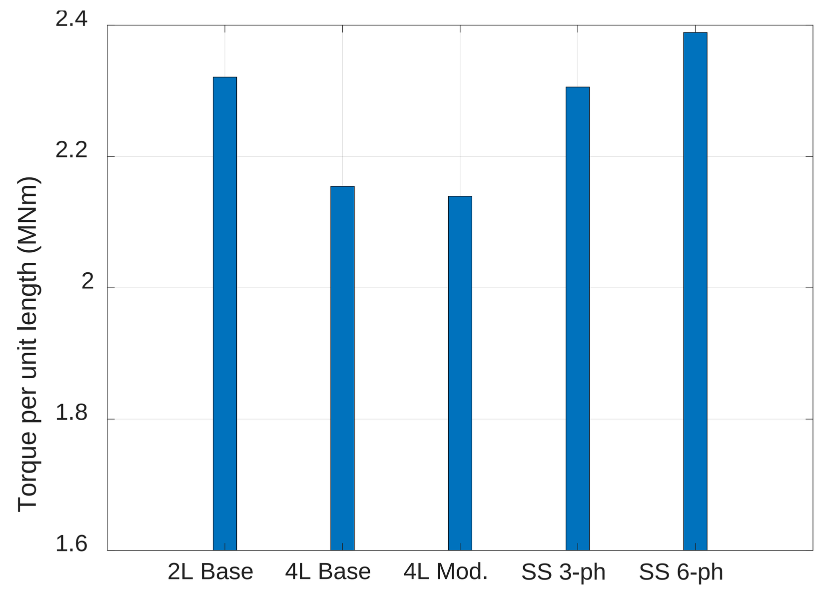
- The 4-layer modified winding eliminated the 1st order of MMF, but the 7th order is still high. This results in a high 12th harmonics of flux density on the HTS field winding.

Stator shifting windings

- The 3-phase winding reduces the 1st order of MMF slightly but effectively reduces the 7th order.
- The 6-phase winding effectively reduces the 7th order of MMF and eliminates the 1st order.

4. Effects on Normal Operation

- Normal operation performance evaluated: torque production, induced losses in the rotor.

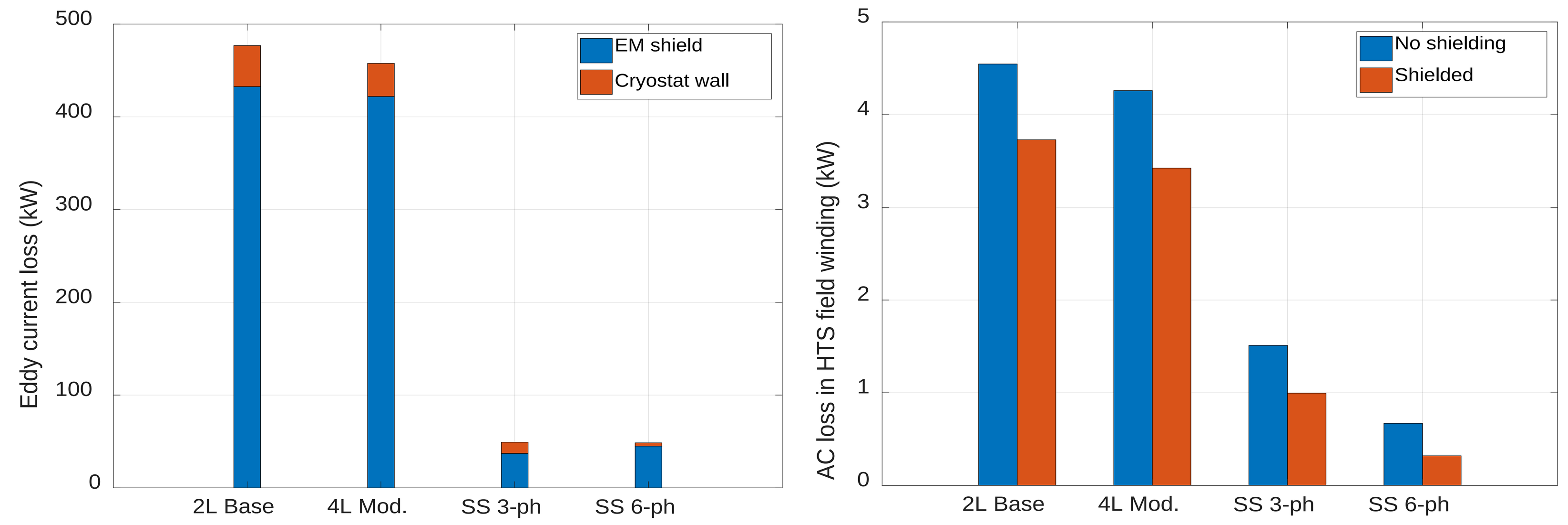


Torque production

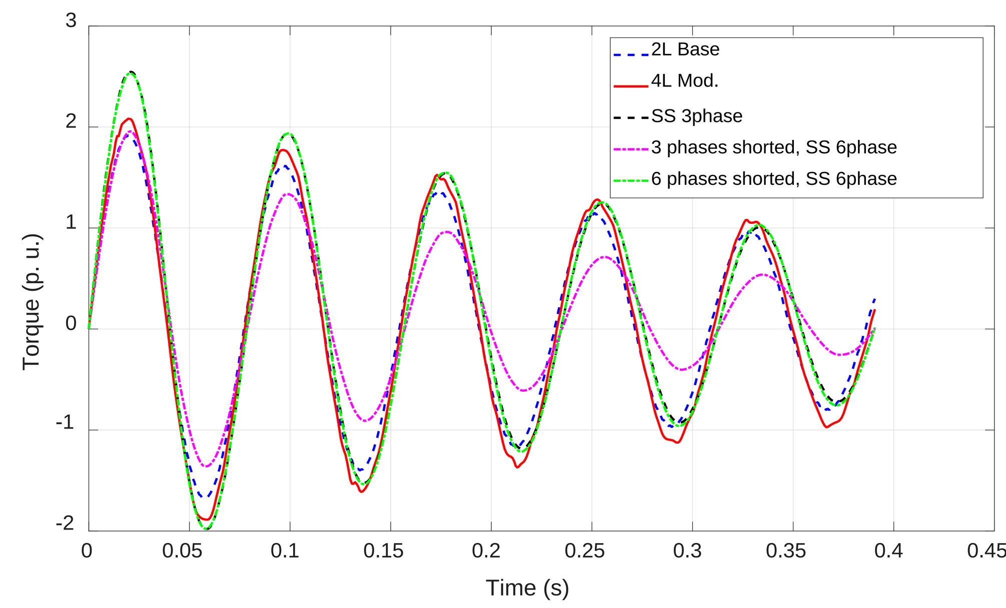
- Generally, the torque production of FSCWs is lower than ISDWs in an HTS generator due to leakage flux.
- The 4-layer windings slightly reduce the torque production, since their winding factors are a bit lower.
- The 3-phase stator shifting produces almost the same torque.
- The 6-phase stator shifting slightly increases the torque production.

Induced losses in the rotor

- The 4-layer modified winding does not effectively reduce the losses.
- The stator shifting can significantly reduces both the eddy current loss and the AC loss.



5. Effects on Short-Circuit Torque



Short circuit torque

- None of the evaluated winding types slight reduce the peak torque, but all torques are below 3 times the rated torque, which is acceptable for wind turbine design.
- Stator shifting increases the peak torque when all phases are shorted.

6. Conclusion

- FSCWs are a candidate for HTS generators in terms of limiting short circuit torque. Space harmonics from FSCWs can be suppressed by applying multi-layer windings and stator shifting windings.
- Multi-layer windings slightly reduce torque production, and the effects on induced losses in the rotor are not significant.
- Stator shifting windings do not reduce torque production, and the effects on induced losses in the rotor are significant, especially the 6-phase one.
- All evaluated winding types keep sufficiently low short circuit torque.
- Among the options studied, the stator shifting winding with 6 phases is the best choice for applying FSCWs to HTS generators.

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