This paper proposes to apply fractional-slot concentrated windings (FSCWs) to HTS generators. 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.

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. 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**: 14 mm
- **No. of turns per pole**: 70
- **Armature current density (RMS)**: 2.6 A/mm²
- **No. of pole pairs**: 80
- **HTS field coil height**: 14 mm
- **No. of slots**: 192 for 4L, 194 for 2L
- **Engineering field current density**: 122 A/mm²
- **Field winding factor**: 0.866x
- **Stator shifting**: 2-layer base winding (2L Base, q = 0.4)
- **4-layer modified winding (4L Mod., q = 0.4)**
- **2-layer base winding (2L Base, q = 0.4)**
- **4-layer modified winding (4L Mod., q = 0.4)**
- **3-phase stator shifting (SS 3-ph)**
- **6-phase stator shifting (SS 6-ph)**
- **The current’s phase shifts by 30°**

### Multi-layer windings

- **Multi-layer windings**
  - 2-layer base winding (2L Base, q = 0.4) based on 10 poles, 12 slots
  - 4-layer modified winding (4L Mod., q = 0.4) based on 10 poles, 12 slots
  - 3-phase stator shifting (SS 3-ph) based on 10 poles, 24 slots
  - 6-phase stator shifting (SS 6-ph) based on 10 poles, 24 slots
  - The current’s phase shifts by 30°

### 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 ISDW 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 reduce both the eddy current loss and the AC loss.

### 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 in the HTS field winding.
- 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.