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Electromagnetic Design of 13.2 MW Fully Superconducting Machine

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Background

Fully superconducting machines can take the most advantages of SC materials with dramatically improving the magnetic loading and electrical loading at the same time. However, intense R&D effort is giving priority to partially SC machines, which only use SC conductors under DC conditions, not only for their lower manufacture difficulty but also higher feasibility compared to fully SC machines. Fully SC machines are in trouble with high ac losses during the operation for too much power is consumed to take away all these heat losses and leakage so as to make an unacceptable low efficiency for the entire system.
Although with many difficulties, the researches of fully SC machines never stop especially when relatively low ac loss SC materials such as fine filament NbTi, BSSCO, and MgB2 were developed. Much work was done by trying new SC materials, and proposing novel topologies to decrease the ac loss or heat leakage.

Objectives

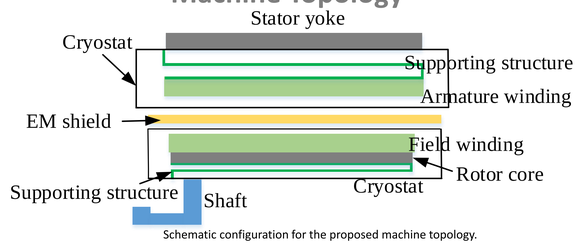
Check the feasibility of fully SC machines by detailed electromagnetic design and multifaceted comparison with partially SC machines.

Conclusion

- A 13.2 MW fully superconducting machine for direct drive wind turbine, with MgB2 windings and low temperature superconducting (LTS) wires on its armature winding and field winding respectively, is proposed and electromagnetic designed.
- Through theoretical analysis and FEA, the performances of the proposed machine are studied and compared with a LTS partially SC machine.
- There are significant advantages of the fully SC machines over the weight of effective parts and the volume of entire system.
- considering more cryogenic refrigerators and supporting structures are needed, the fully SC machines will cost much more than partially SC machine, which becomes the most obstacle in the development of the former ones

Electromagnetic Design

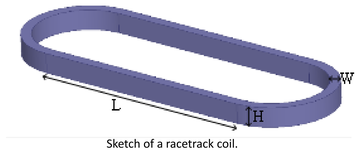
Machine Topology



Schematic configuration for the proposed machine topology.

- Ferromagnetic teeth, rotor core, and stator yoke.
- Separated vacuum cryostat for field winding and armature winding.
- Cold rotor iron core and warm stator yoke.
- Main design parameters: rated power 13.2 MW, rated speed 9 rpm, rated phase current 1.64 kA, rated phase voltage 2.73 kV.

Field Winding Design



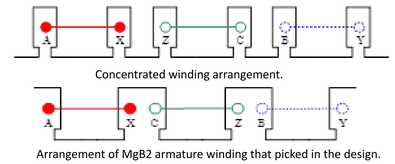
Sketch of a racetrack coil.

- Racetrack coils are adopted to make LTS magnets.
- The highest magnetic flux density at the LTS magnets is lower than 8 T.
- Ferromagnetic teeth are used to reduce the magnetic field density on the superconductors.
- The operating current is about 80% of the critical current for the iron core can improve the safety factor of the SC magnets.

MAIN SPECIFICATIONS OF ROTOR ASSEMBLY

Parameter	
Field winding superconductor	NbTi/Cu
Superconductor dimension(mm)	0.7 X 1.28
Operating temperature(K)	4.2
Coolant	LHe
Operating current(A)	197
Inner radius of field winding(mm)	1645
Outer radius of field winding(mm)	1712
Number of turns per pole	5100
Mean length per turn(m)	2.44
Total MMF(kA)	80376
Total superconductor usage(km)	248.5

Armature Winding Design



Concentrated winding arrangement.

Arrangement of MgB2 armature winding that picked in the design.

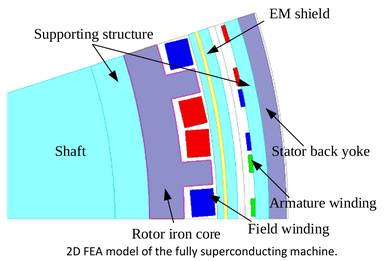
- To prevent MgB2 wires from current deterioration by bending strain, concentrated windings are employed.
- The maximum magnetic field density over the armature winding is about 2.5 T .
- To lower the AC losses and increase the heating surface area, the operating current of the MgB2 winding is set to 410 A, which is far away from the critical point.

MAIN SPECIFICATIONS OF STATOR ASSEMBLY

Parameter	
Armature winding superconductor	MgB_2
Superconductor dimension(mm)	1.3 X 1.3
Operating temperature(K)	20
Coolant	GHe
Operating current(A)	410
Inner radius of armature winding(mm)	1818
Outer radius of field winding(mm)	1830
Inner radius of stator yoke(mm)	1870
Outer radius of stator yoke(mm)	1920
Number of Coils	60
Number of turns per coil	240
Mean length per turn(m)	2.28
Total superconductor usage(km)	32.8

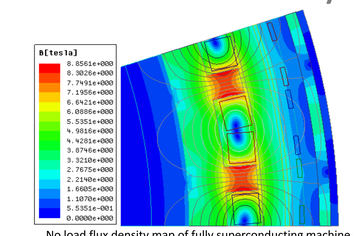
FEA Results and Comparison

FEA and Efficiency Estimation

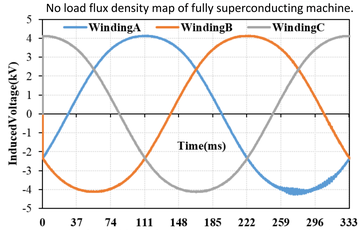


2D FEA model of the fully superconducting machine.

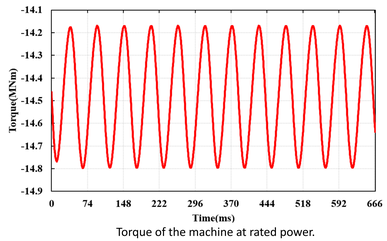
- 1/20 model of the machine was constructed.
- The sinusoidal waveforms of three phase armature winding induced voltage proves that the proposed machine can work normally.
- The rotor iron core and the stator back iron yoke are both in highly saturated. Outside the stator back yoke, the magnetic field is around 0.5 T and a good shielding effect the machine has.
- The average electromagnetic torque is 14.5 MNm and the torque ripple is 4.3%.



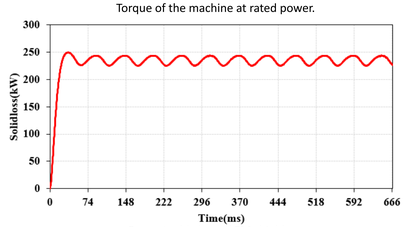
No load flux density map of fully superconducting machine.



No-load EMF of the fully superconducting machine



Torque of the machine at rated power.



Current eddy loss of EM shield.

The core loss in stator back core and rotor iron core, and the eddy loss in the EM shield can be get from the FEA results. The core loss of stator back core came out to be 2.05 kW and that of rotor iron core came out to be 1.93 W.

The external magnetic field AC losses of armature winding was estimated by $P_{ACloss} = f \times L \times Q$
The external magnetic field AC loss is 2.2 kW and the self-field one is 0.73 kW. The total AC loss is estimated to be 2.93 kW.

The efficiency of the proposed machine is about 95.7% after considering all the losses expect mechanical losses.

Comparison with LTS Superconducting Machine

MAIN PARAMETERS OF SPECIFICES COMPARISON

Parameter	Fully SC machine	LTS SC machine
Stator outer diameter(m)	3.94	7.23
Rotor outer diameter(m)	3.5	6.4
Axial effective length(m)	0.95	1.05
Magnetic loading(T)	2.5	2.2
Usage of SC conductors(km)	NbTi/Cu: 248.9 MgB_2: 33	NbTi/Cu: 920
Air-gap length (mm)	100	85
Armature winding current density(A/mm^2)	293	3
Weight of silicon steel (t)	31	48
Weight of condutors (t)	2.5	28.4
Estimated weight of supporting structure(t)	97.2	64.1
Cost of the effective parts(k$)	194	590
Estimated cost of cryogenic refrigerators(k$)	1120	632.3

The 13.2 MW LTS partially SC machine was designed for offshore direct-drive wind turbines. The field windings of the machine are wound by NbTi/Cu wires, and armature winding are using copper. The field windings are fixed by non-ferromagnetic formers.

- For the effective parts, the fully SC machines are superior to partially SC machines.
- A preliminary analysis of the cryogenic refrigeration system shows that more heat load should be taken away from the fully SC machine, which takes the most important share of the initial cost.
- The supporting structures are needed both on the stator and rotor side, which nearly double the weight of it.
- The cost and weight of effective part in fully SC machine are lower than ones in partially SC machine, the total cost of the former one is much higher than the later considering the high cost of ancillary parts.

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