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3D Modeling of an All-Superconducting Synchronous Electric Machine by the Finite Element Method

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All-Superconducting Synchronous Electrical Machines

- **All-superconducting synchronous electrical machine:**

Superconducting stator using High Temperature Superconducting (HTS) Coils

+ Superconducting rotor (also HTS Coils)

- **Advantages:**

Higher current density → increased power density → reduced size & weight

Lower wire resistance → lower losses & higher efficiency / better performance

AC Loss in Superconducting Coils

- **Finite, hysteretic AC loss appears for time-varying current and/or magnetic field**
- Stator experiences alternating current / time-varying magnetic field → AC loss exists.
- Rotor experiences DC current. AC loss does **not** exist.
- AC loss amplified at low temperatures, e.g., $\mathbf{P_{actual} \approx 20\ P_{77\ K}}$
- Investigating methods to calculate and decrease the AC losses in the HTS stator of all-superconducting machine are important.

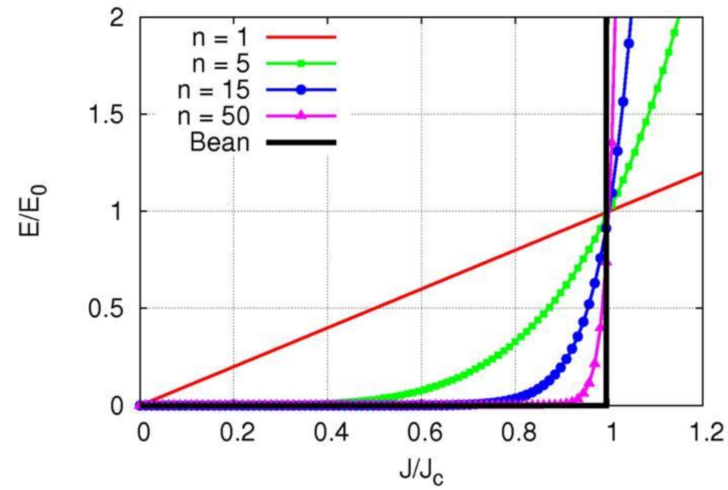
Governing Equations in COMSOL Multiphysics

- Maxwell's equations (H formulation) + non-linear *E-J* Power law

$$\nabla \times \boldsymbol{E} + \mu_0 \mu_r \frac{\mathrm{d}\boldsymbol{H}}{\mathrm{d}t} = 0 \qquad \nabla \times \boldsymbol{H} = \boldsymbol{J} \qquad \boldsymbol{E} = E_0 \left(\frac{\boldsymbol{J}}{J_c}\right)^n$$

- AC loss calculation:

$$Q_{ac} = \frac{1}{V}\int_0^T \mathrm{d}t \int_0^V \boldsymbol{E} \bullet \boldsymbol{J}\,\mathrm{d}v$$



- Ferromagnetic material properties:

$$\mu_r(H_{norm}) = 1 + 1200000(1 - \exp(-(H_{norm}/70)^{3.2}))H_{norm}^{-0.99}$$

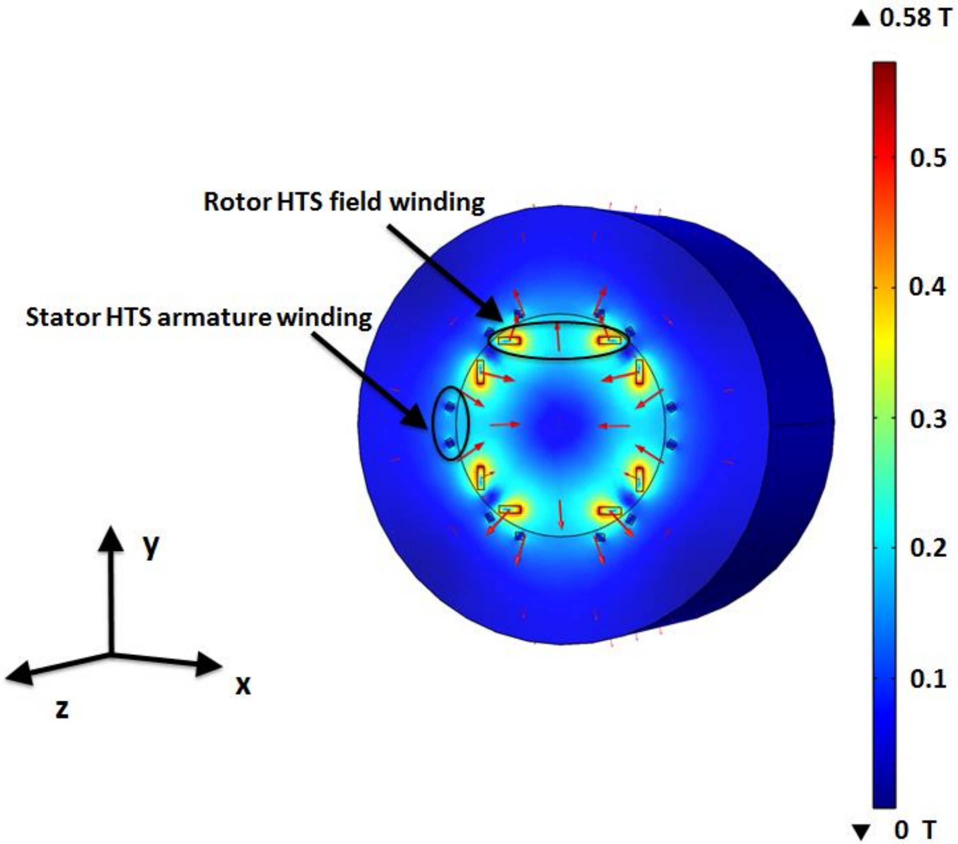
$$Q_{ferro}(B_{max}) = 171.2 B_{max}^{1.344} \qquad 0.1 \le B_{max} \le 1.53$$

From measured data

Motor Parameters

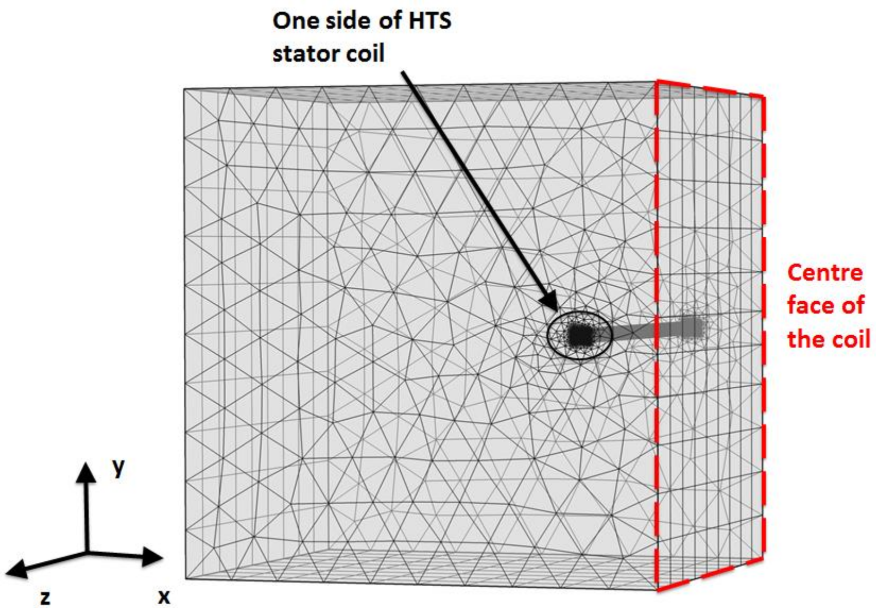
PARAMETERS	SYMBOL	VALUE
Pole-pairs	p	2
Phase number	m	3
Rotor radius	R_r	130 mm
Field winding coil turns (rotor)	N_r	300
Field winding coil thickness (rotor)	h_r	9 mm
Field winding coil width (rotor)	w_r	30 mm
Distance between field coil sides (rotor)	W_r	106 mm
Armature winding position radius	R_s	153 mm
Armature winding coil turns (stator)	N_s	110
Armature winding coil thickness (Stator)	h_s	9 mm
Armature winding coil width (Stator)	w_s	11 mm
HTS wire critical current (77 K, self-field)	I_c	100 A
Operating temperature	T_{op}	77 K
Motor length	L	300 mm

3D Machine and Stator Coil Model



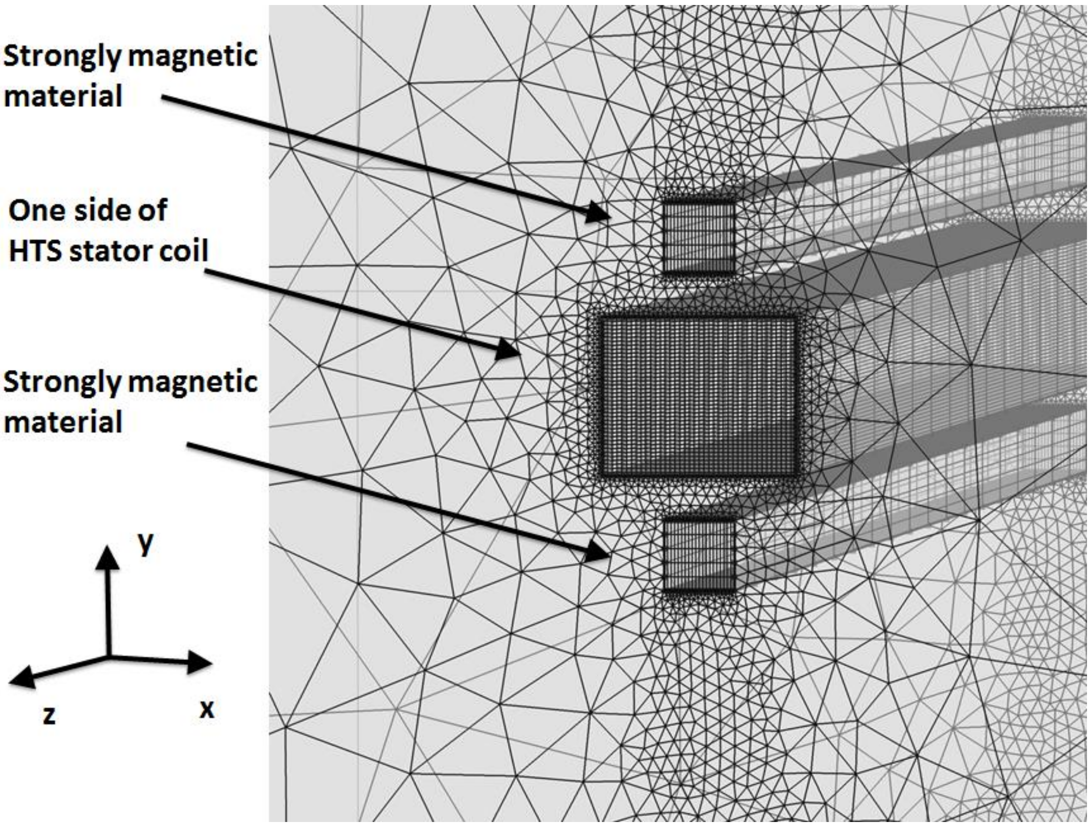
3D HTS machine model

Magnetic boundary conditions for the 3D stator coil model are derived from the 3D HTS machine model



3D stator coil model

Use of Flux Diverter – AC Loss Reduction

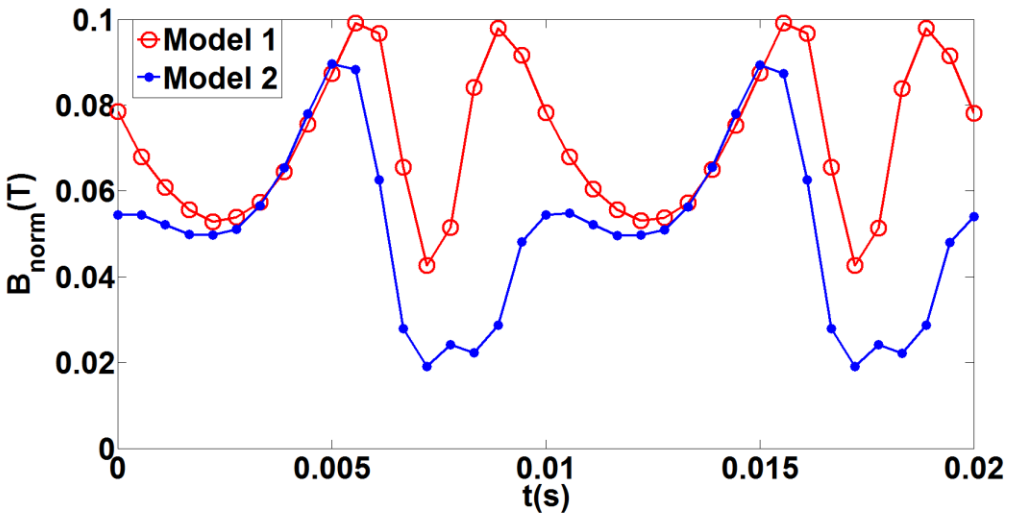


- Magnetic materials are added at the top and bottom of the coil

- The width of the flux diverter is shorter than the width of the coil →

  Avoids a relatively higher local magnetic field at the innermost turn of the coil, which decrease the critical current of the coil

Simulation Results



Model 1	**HTS Models without flux diverter**
Model 2	HTS Models with flux diverter

Magnetic field, B_{norm}, seen by the stator coil as the rotor rotates from its initial position through 180° (half a revolution)

Conclusion: flux diverters can help decrease the magnitude of the average external magnetic field seen by the stator coil

AC Loss Comparison With & Without Flux Diverters

	MODEL 1 No diverter	MODEL 2 Diverter
Magnetization loss	296 J/cycle	276 J/cycle
Transport loss	765 J/cycle	720 J/cycle
Ferromagnetic material loss	0 J/cycle	3.8×10^{-3} J/cycle

Conclusions:

- **Flux diverters can help decrease both the magnetization loss and transport losses**
- **Although the ferromagnetic material has hysteresis loss, this is small & can be ignored compared with the AC loss in the HTS material**

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Thank you for your attention