HTS2018 MODELLING

Simulation of Synchronous-Hysteresis Superconducting Machine

Bárbara M. O. Santos[1], Fernando Dias[1,3], Felipe Sass[2], Guilherme Sotelo[2], Alexander Polasek[3] and Rubens de Andrade Jr[1]

[1]Federal University of Rio de Janeiro (UFRJ)

[2]Federal Fluminense University (UFF)

[3]Electric Power Research Center (CEPEL)

Outline

1. Motivation
2. Studied prototype
3. Objectives
4. Simulation Models
5. Results
6. Conclusion

Motivation

- Several works in the literature have proposed replacing HTS bulks by HTS 2G tapes in trapped field motors*

Trapped field rotors

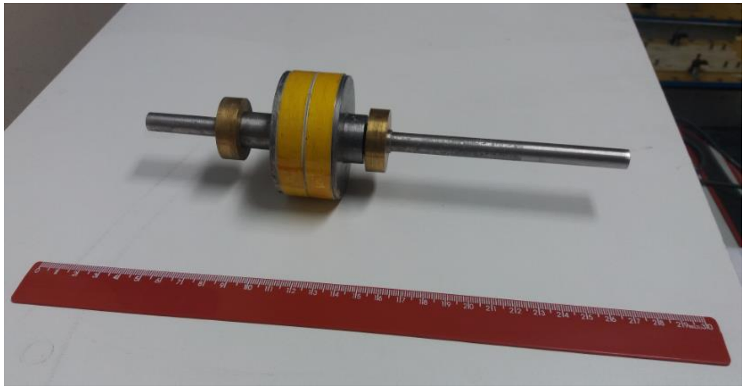
With bulks

With HTS tapes

*G.G. Sotelo, F. Sass, M. Carrera, J. Lopez-Lopez and X. Granados. Proposal of a Novel Design for Linear Superconducting Motor Using 2G Tape Stack. *IEEE Transactions on Industrial Electronics.,* vol 65, no 9, Sept. 2018.

Studied Prototype

Prototype built at UFRJ and CEPEL. Non-superconducting three-phase stator and rotor made of two rings of **nine turns of HTS 2G tapes** wrapped around a ferromagnetic cylinder.



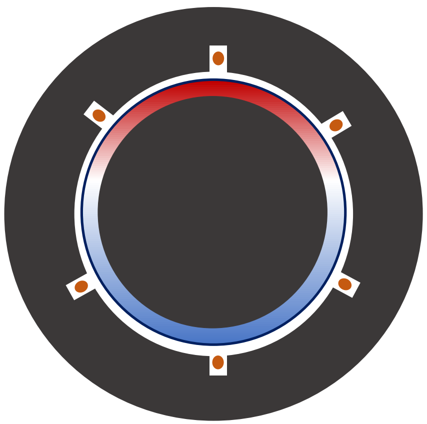
Adapted from a 0.47Nm Permanent Magnet Machine

Maximum radius	56 mm
Length	28 mm
Tape	SuperPower SF12050
Phases and Poles	3 Phases, 6 Poles
Critical current measured	377 A

Studied Prototype

Trapped Field Motor with HTS 2G Tapes

Superconductor is magnetized by the rotating magnetic field applied



The mode of operation depends on the mechanical torque

$$\tau_{mec} < \tau_{pinning} \longrightarrow \omega_{mec} = \omega_{sinc}$$

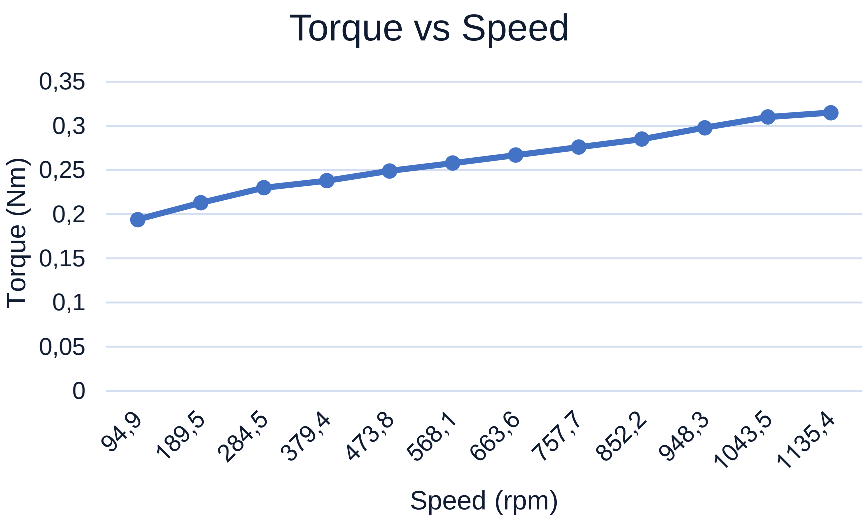
Synchronous machine

$$\tau_{mec} > \tau_{pinning} \longrightarrow \omega_{mec} < \omega_{sinc}$$

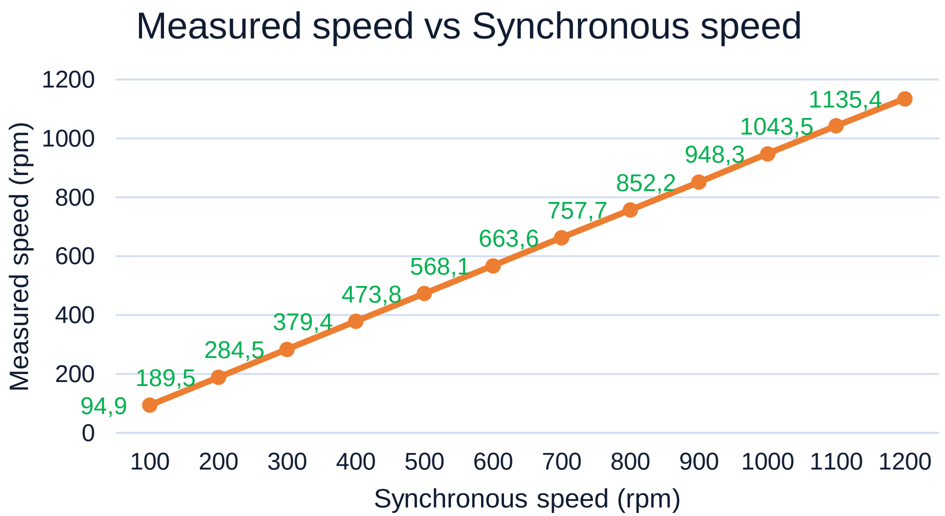
Hysteresis machine

Studied Prototype

Experimental data



Mechanical torque applied.



5% slip appeared in the torque vs speed curve

Objectives

- Observe the induced current density in the rings at locked rotor ➡ H Formulation
- Analyse machine behavior at synchronous speed ➡ A-V Formulation
- Analyse the dynamic response ➡ Mixed A-V-H Formulation

Simulation Models

Simulation Models: H Formulation

COMSOL's Magnetic Field Formulation

$$\nabla \times \mathrm{H} = \mathrm{J}$$

$$\frac{\mu \partial \mathrm{H}}{\partial \mathrm{t}} + \nabla \times \mathrm{E} = 0$$

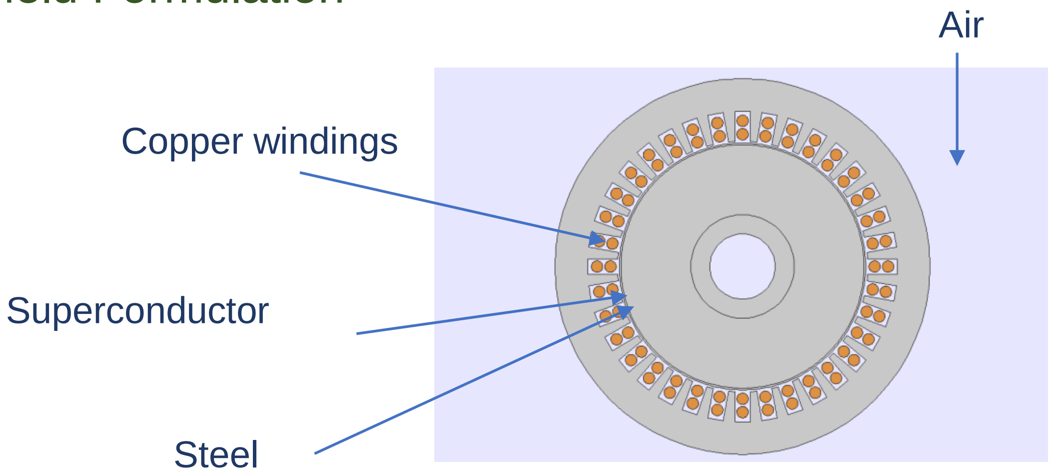
$$E(J) = E_c \left| \frac{J}{J_c} \right|^{n-1}$$

J_c Homogeneized

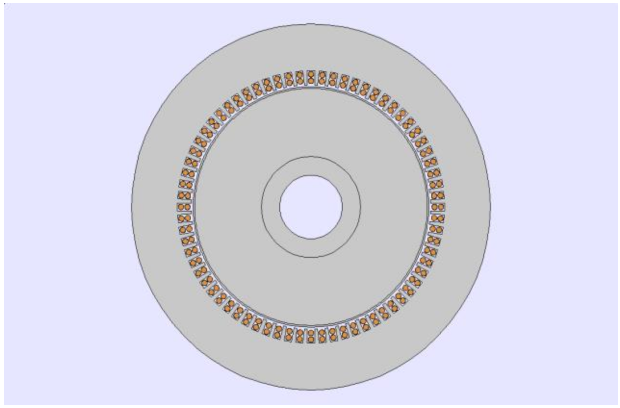
At the boundary, $H_x = H_y = 0$

Linear B-H curve for all materials

Considering Flux-Creep region, zero field cooling



36-slot stator



72-slot stator

Simulation Models: A-V Formulation

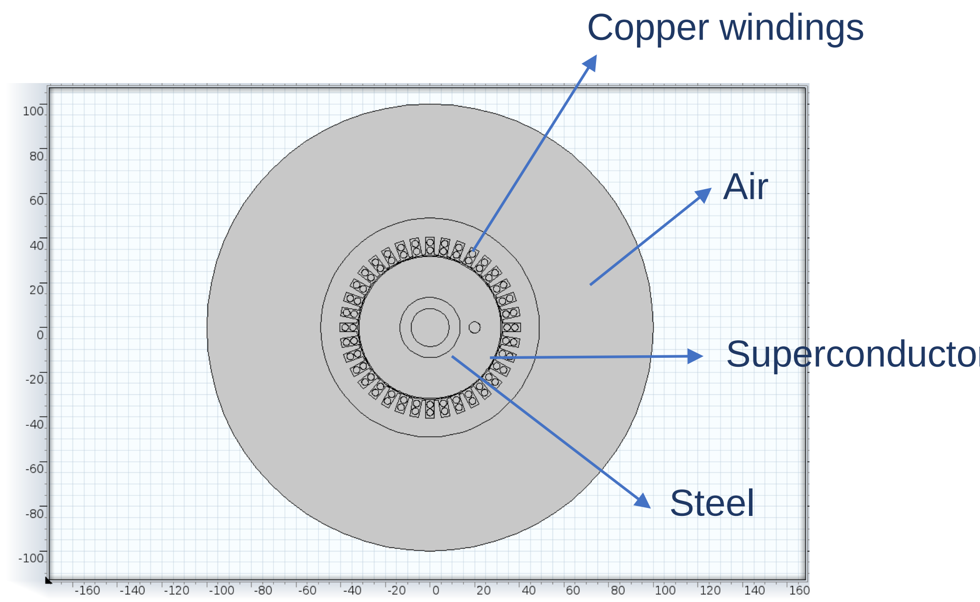
COMSOL's Rotating Machinery, Magnetics

$$\sigma \frac{\partial A}{\partial t} + \nabla \times H = J_{ext}$$

$$B = \nabla \times A$$

$$\nabla \cdot (\mu_0 \mu_r H) = 0$$

$$\sigma = \frac{J_c}{E_c} \left| \frac{E + E_0}{E_c} \right|^{\frac{1-n}{n}}$$



$$J_c(B) = \frac{J_{c0}}{\left(1 + \frac{B_r}{B_0}\right)^{\beta}}$$

Homogeneized

At the boundary, $A_z = 0$

Considering Flux-Creep region, zero field cooling

Simulation Models: Mixed Formulation*

COMSOL's General and Coefficient PDEs

$$\sigma \frac{\partial A}{\partial t} - \frac{1}{\mu} \nabla^2 A = J_{ext}$$

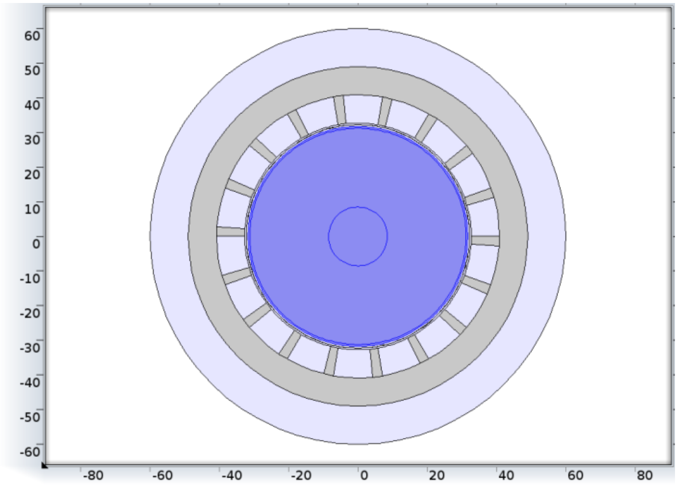
$$B = \nabla \times A$$

Stator, Rotor air gap

$$\frac{\mu \partial H}{\partial t} + \nabla \times E = 0$$

$$\nabla \times H = J$$

Rotor



$$H_t^A = H_t^H \qquad \rho(J) = \frac{E_c}{J_c} \left| \frac{J}{J_c} \right|^{n-1}$$

J_c Homogeneized

Considering Flux-Creep region, zero field cooling

*R. Brambilla, F. Grilli, L. Martini, M. Bocchi and G. Angeli. A Finite Element Method Framework for Modeling Rotating Machines With Superconducting Windings. *IEEE Trans. Appl. Supercond.,* vol 28, no 5, Aug. 2018.

Simulation Models: Mixed Formulation*

The mechanical model was implemented with COMSOL's Global ODEs and PDE's and Moving Mesh

$$T_{elect} - T_{mec} = \frac{Jd\omega}{dt}$$

A few remarks:

- A simpler stator was used;
- The stator moves in the opposite direction.

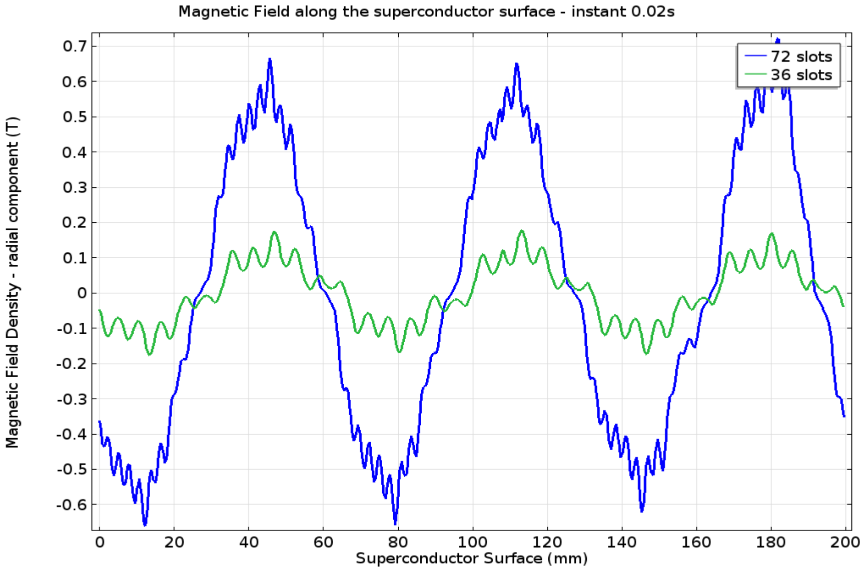
} Convergence
Simulation time

Results

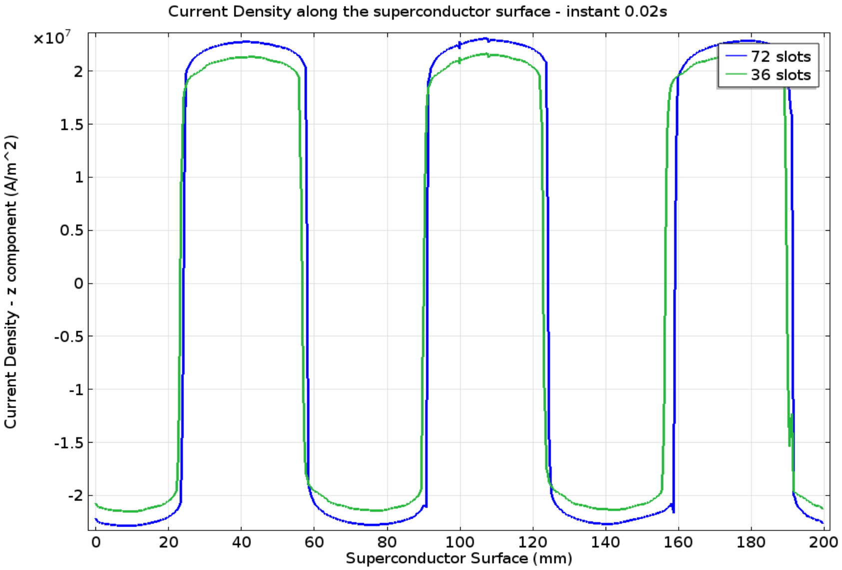
Results: H Formulation Model

$J_c = 2.98 \; x \; 10^7 \; A/m^2$, f = 60Hz, n=25, locked rotor

Magnetic Field along the air gap



Induced Current Density – z component along the supercondutor ring

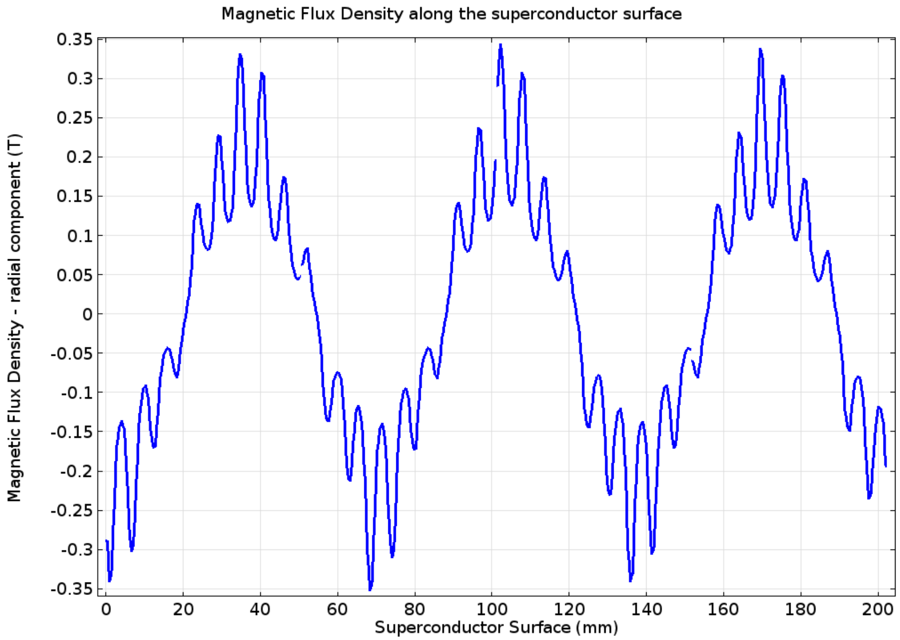


Influence of field harmonics are low in the induced current density

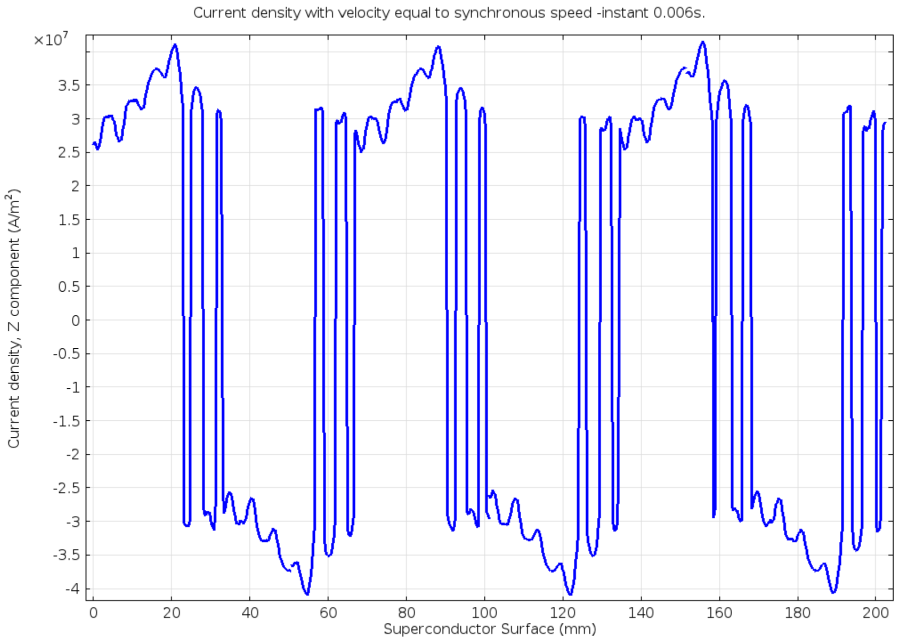
Results: A-V Formulation Model

$J_{c0} = 2.98\,x\,10^{7}\,A/m^{2}$, $B_0 = 0.5T, \beta = 1, f = 60Hz$, n=25, synchronous speed

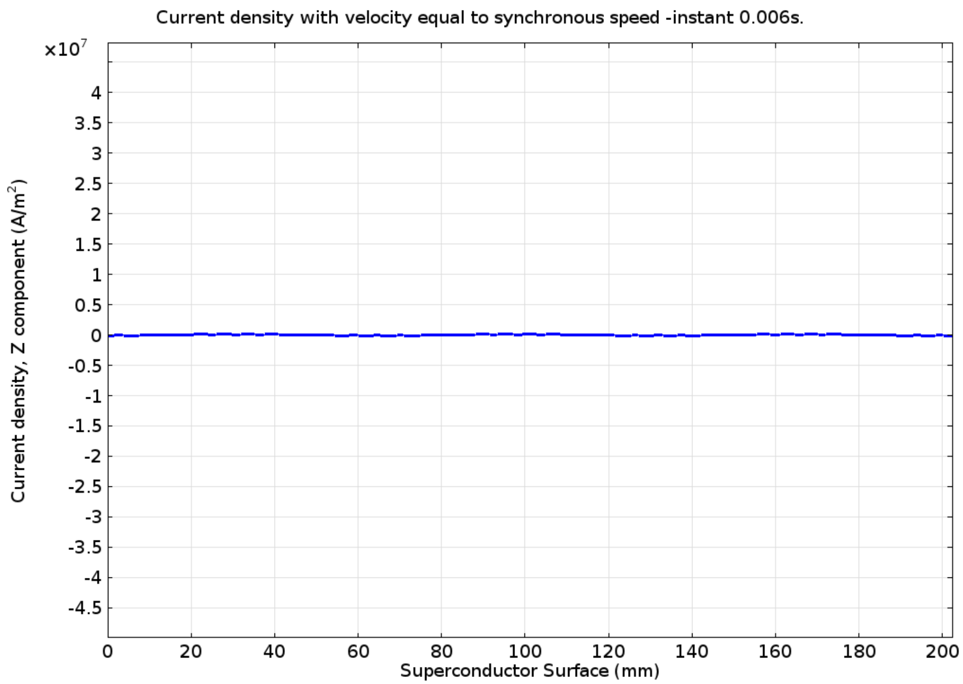
Magnetic Field along the air gap



Induced Current Density along the Superconductor ring



Results: A-V Formulation Model

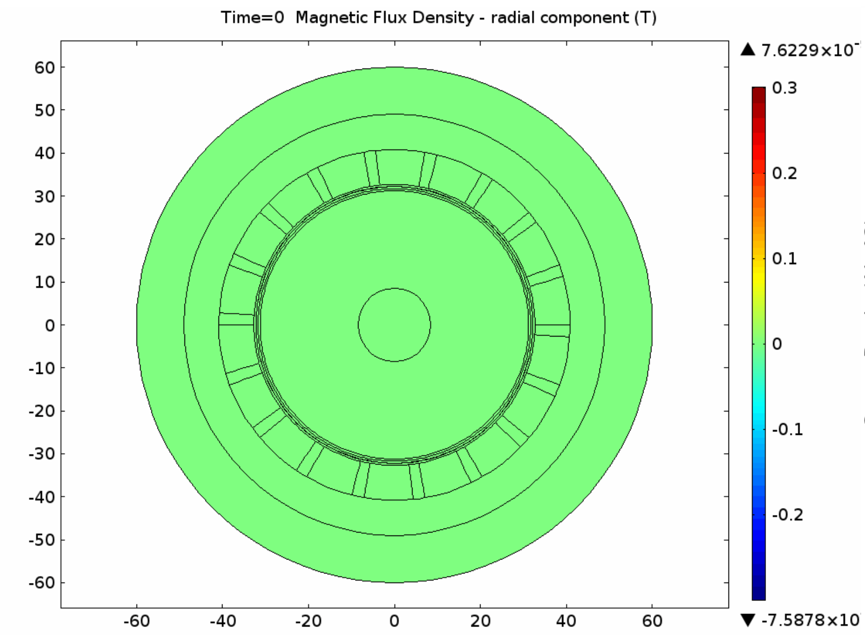


- Many disturbances at synchronous speed, but amplitude stays the same
- Many convergence problems arise

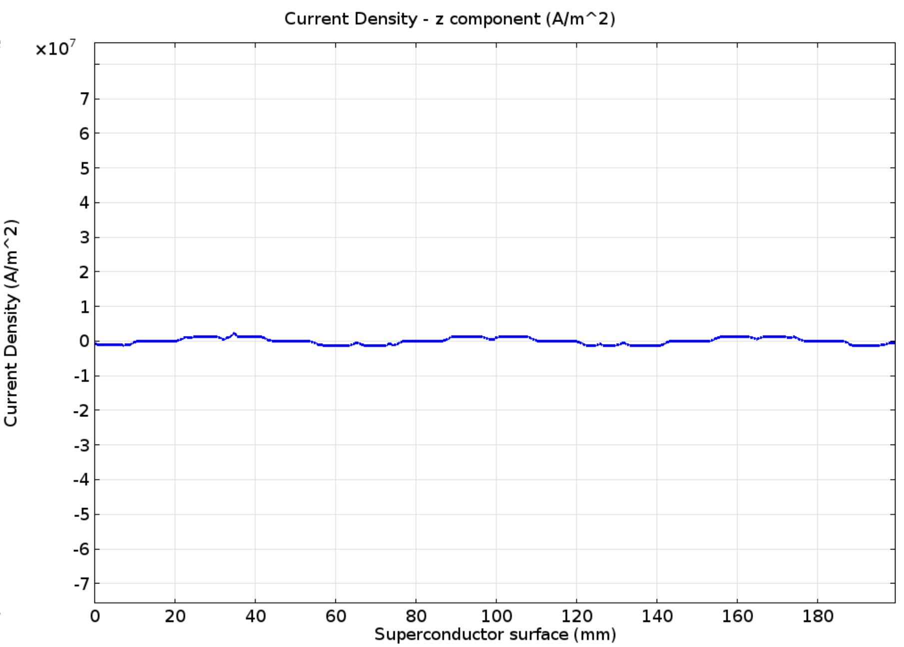
Results: Mixed Formulation Model

$J_{c0} = 3.437\ x\ 10^7\ A/m^2$, f $= 60$Hz, n=25, no load condition

Magnetic Field – radial component



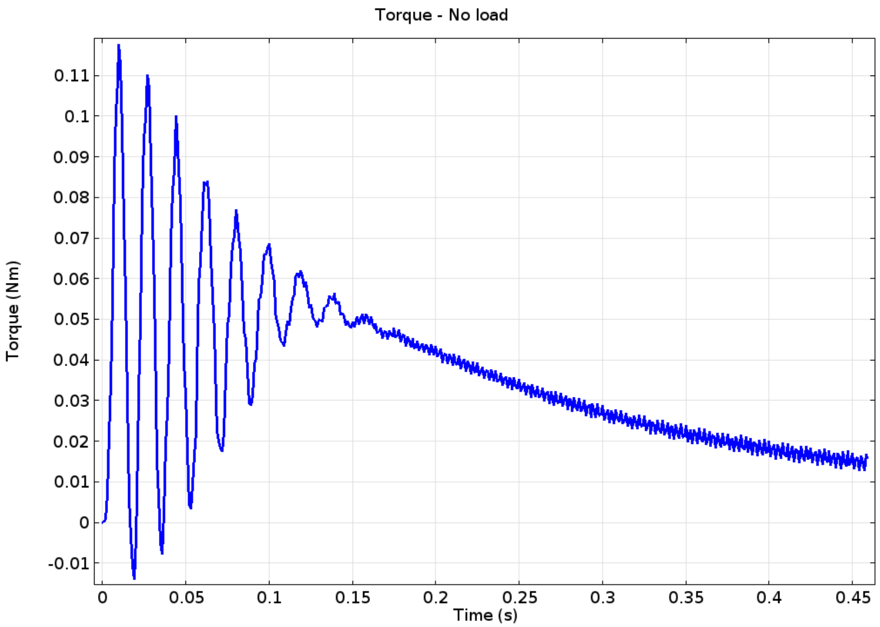
Current Density along the Superconductor ring



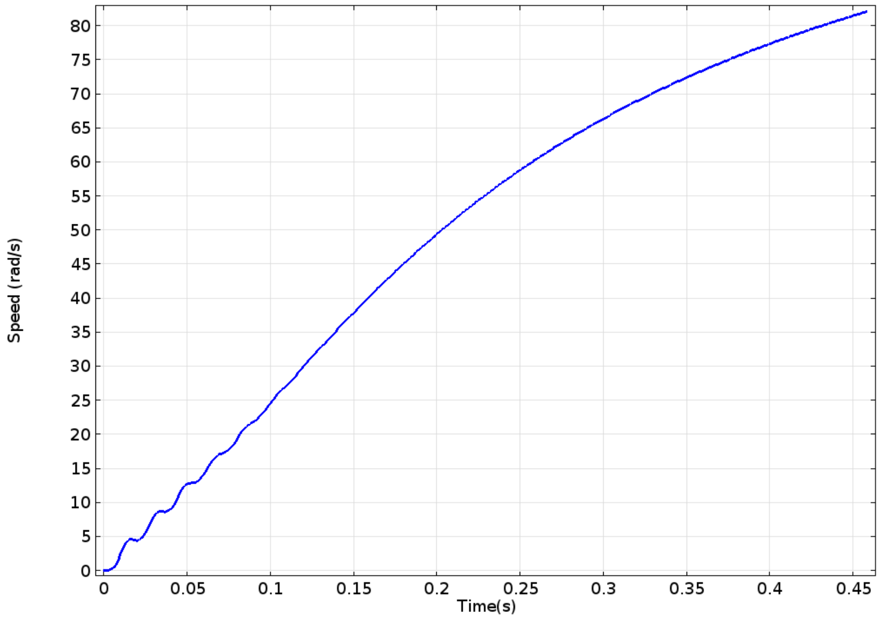
Results: Mixed Formulation Model

$J_{c0} = 3.437x\ 10^7\ A/m^2$, $\mathrm{f} = 60\mathrm{Hz}$, n=25, no load condition

Torque vs Time



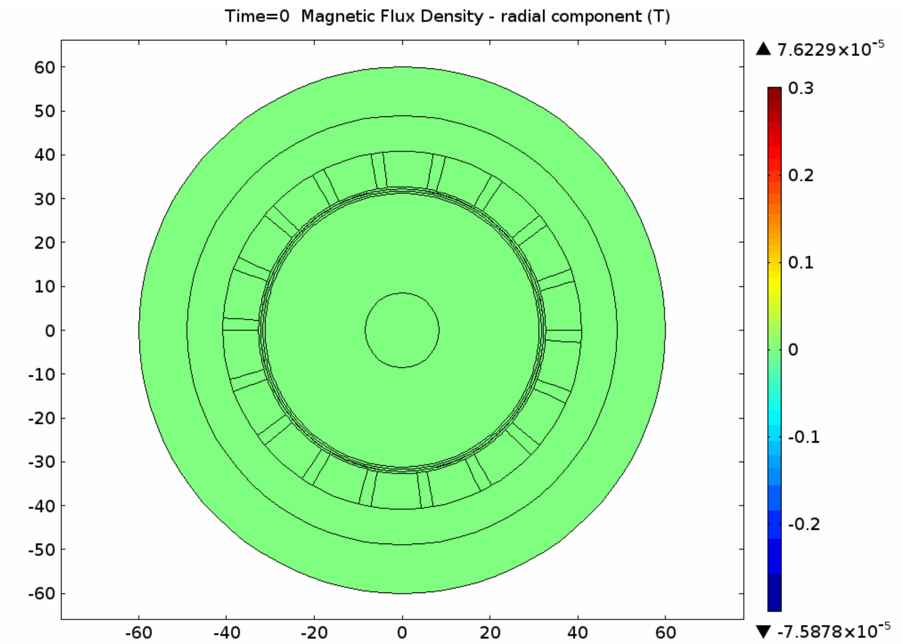
Speed vs Time



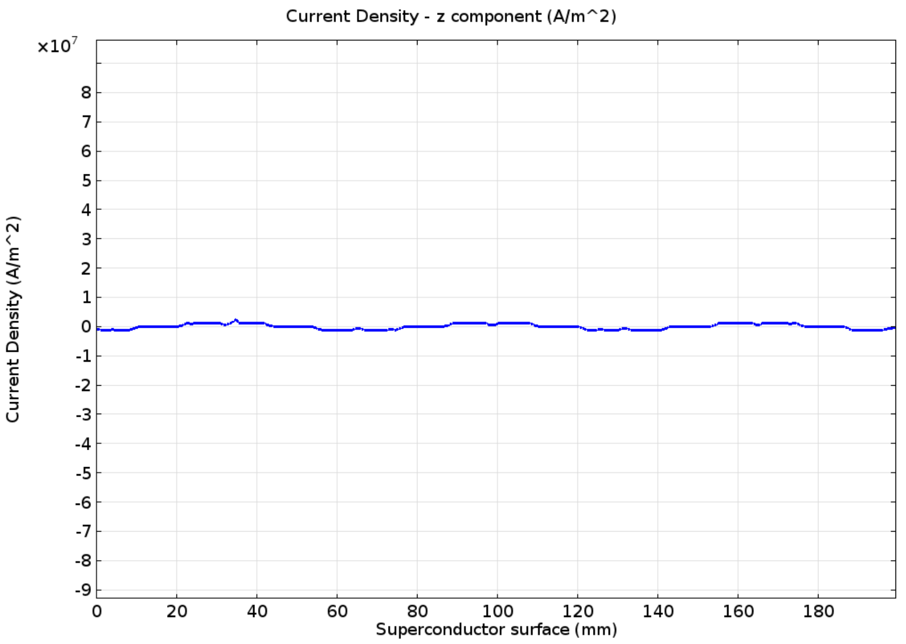
Results: Mixed Formulation Model

$J_{c0} = 3.437x\ 10^7\ A/m^2$, f = 60Hz, n=25, load condition

Magnetic Field – radial component

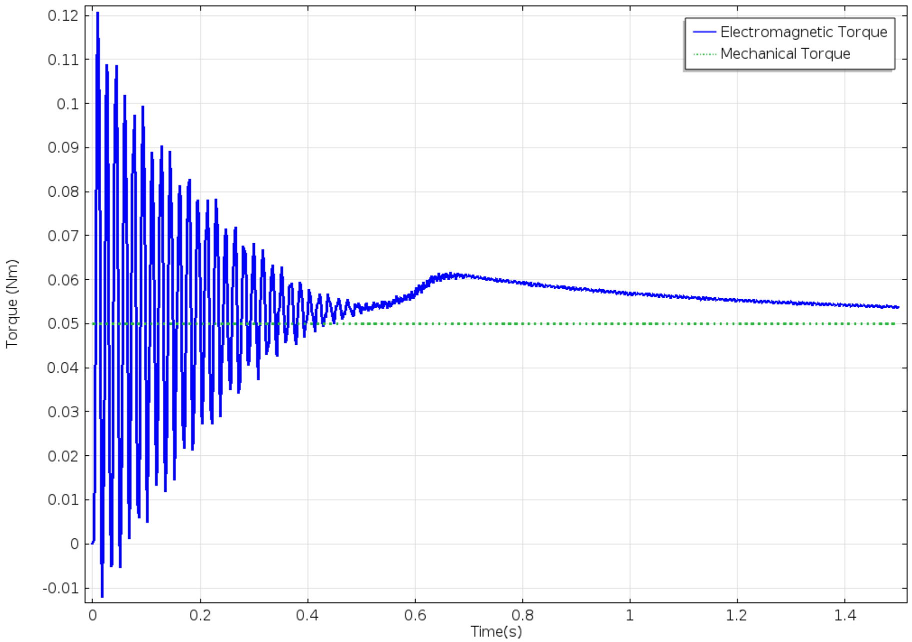


Current Density along the Superconductor ring

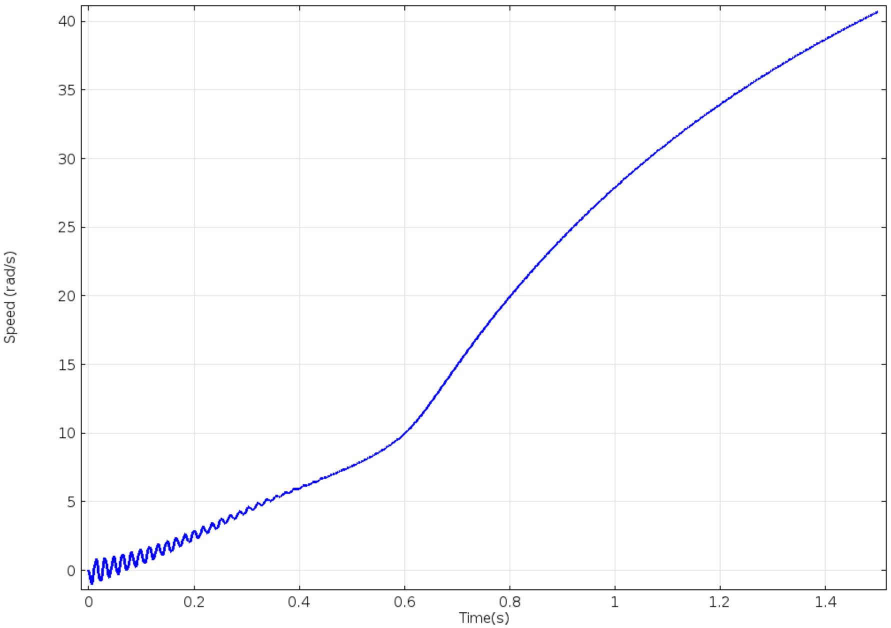


Results: Mixed Formulation Model

Torque vs Time



Speed vs Time



Conclusion

- Air-gap magnetic field harmonics have little impact on the induced current density;
- As speed increases, the current density distribuition along the ring increases;
- The hysteresis region is larger than expected;
- The speed response is overdamped.

Thank You!

Bárbara M. O. Santos

MSc. Student

barbara.maria@poli.ufrj.br

Support