Simulation of the interaction between a 2G HTS stack and a traveling inhomogeneous magnetic field

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Outline

- Motivation
- Objectives
- Introduction
- The model
- Results
- Final Considerations
Motivation: Electric Machines with stacks of 2G tapes

X. Granados et al. EUCAS-2015, Lyon.

Objectives

• To simulate the interaction between a travelling inhomogeneous magnetic field and a 2G tape HTS stack

• To compare the simulated results with measurements

• To extrapolate the model to investigate the influence of some parameters change
Trapped field motors

The magnetic field rotates and the superconductor magnetizes (partially or fully) according to the applied magnetic field.

\[ \tau_{\text{load}} < \tau_{\text{pinning}} \]

A) Synchronous machine (no losses in steady state)
- the resistant torque is smaller than that allowed by the electromagnetic forces and the pinning of the magnetic flux;
- The rotor moves in the synchronous speed;

\[ \tau_{\text{load}} > \tau_{\text{pinning}} \]

B) Hysteresis machine (Losses)
- the resistant torque is larger than that allowed by pinning of the flux and the electromagnetic forces;
- The rotor moves slower than the synchronous speed (there is a slip);
2G HTS Electric Motors

The rotational machine

Linear case studied here

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Studied System

Schematic

Exp. set up

Stack

SuperPower
SF12050-AP (2013)

$I_{c\text{, av.}} = 281$ A (Self Field, 77 K)

$n = 35$ (Self Field, 77 K)

9 layers

Width = 12 mm

Length = 30 mm

Thickness total = 510 $\mu$m
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The H-formulation (2D)

\[ H_z = E_x = E_y = J_x = J_y = 0 \]

\[ \rho = \frac{1}{\sigma} = \frac{E_c}{J_c} \left| \frac{E}{E_c} \right|^{1-1/n} = \frac{E_c}{J_c} \left| \frac{J}{J_c} \right|^{n-1} \]

\[ \mu \frac{\partial H_x}{\partial t} + \nabla \times E = 0, \]

\[ J = \nabla \times \nabla. \]

\[ \frac{\partial E_z}{\partial y} - \frac{\partial E_z}{\partial x} = 0, \]

\[ J_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}. \]

\[ E_z = \rho J_z \]

\[ J_z = J_c (B) \]
The H-formulation (2D): FEM-BEM

H-Formulation with edge elements: boundary conditions

\[ H_x = H_{x \text{ ext.}} + H_{x \text{ HTS}} \]
By Biot-Savart’s law:
\[ \frac{1}{2\pi} \int \int_{a}^{b} \int_{-a}^{b} J_z(x,y) \frac{\Delta y}{r^2} \, dx \, dy \]
By analytic equation

\[ H_y = H_{y \text{ ext.}} + H_{y \text{ HTS}} \]
By Biot-Savart’s law:
\[ \frac{1}{2\pi} \int \int_{a}^{b} \int_{-a}^{b} J_z(x,y) \frac{\Delta x}{r^2} \, dx \, dy \]
By analytic equation

Permanent Magnets Analytic Equations

\[ H_x(x,y) = \frac{M}{4\pi} \ln \left[ \frac{(y_1 - y_3)^2 + (x_1 - x_3)^2}{(y_1 - y_4)^2 + (x_1 - x_4)^2} \right] \]

\[ H_y(x,y) = -\frac{M}{2\pi} \arctan\left( \frac{y_1 - y_3}{x_1 - x_3} \right) + \frac{M}{2\pi} \arctan\left( \frac{y_1 - y_2}{x_1 - x_2} \right) - \frac{M}{2\pi} \arctan\left( \frac{y_1 - y_4}{x_1 - x_4} \right) + \frac{M}{2\pi} \arctan\left( \frac{y_1 - y_5}{x_1 - x_5} \right) \]

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Magnetic Field Results

Central measured line

Adjusted External Field (@77K)

Hall mapping (@77K)
Results
Stack displacement

The stack was displaced at a constant speed:

\[ x \]

Two speeds were measured to be compared with simulations:
\[ v_1 = 0.344 \text{ mm/s}; \]
\[ v_2 = 0.2066 \text{ mm/s}. \]
Homogenized domains and induced currents

- 1 Domain

- 3 Domains

- 9 Domains

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Force Results: \( v = 0.344 \text{ mm/s} \)

\[ I_c = 281 \text{ A} \]
\[ n = 35 \]

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<th>Domains</th>
<th>DOF</th>
<th>Comp. time</th>
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<td>1</td>
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<td>77 min</td>
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<tr>
<td>9</td>
<td>1689</td>
<td>123 min</td>
</tr>
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i7, 3.9GHz, 16 Gb RAM

i7, 3.9GHz, 16 Gb RAM
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**Force Results:** $v = 0.207 \text{ mm/s}$

$I_c = 281 \text{ A} \\
\eta = 35$

<table>
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<th>DOF</th>
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</tbody>
</table>

i7, 3.9GHz, 16 Gb RAM
**Force Results: n influence**

\[ I_c = 270 \, \text{A} \]
\[ v = 0.344 \, \text{mm/s} \]
Force Results: $I_c$ influence

$n = 35$
$v = 0.344 \text{ mm/s}$
Force Results: speed influence

$I_c = 281$ A

$n = 35$
Final Considerations

• The H-formulation with FEM-BEM is an interesting way for modelling the interaction between a traveling magnetic field and a stack of 2G HTS tapes

• The model can be applied to the project HTS machines (stacks or bulks)

• It was possible to calculate very fast the proposed problem (~30 min, 1 domain)

• The model was extrapolated and some parameters were changed to investigate their influence into the force
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