Modelling Considerations for Trapped Flux-Type Superconducting Electric Machine Design

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Presentation Outline

• Superconducting Applications for Electric Power Systems

• Superconducting Machine Research
  • Modelling considerations for high temperature superconducting (HTS) tape / bulk materials
    • *Stator*: AC loss in superconducting coils
    • *Rotor*: Bulk superconductors as trapped field magnets
Electrical Engineering Applications

- Energy security & supply is a crucial 21st century challenge
- US DOE estimates > 35 trillion kWh required worldwide by 2035 \[1\]
  - 1.8 billion middle-class consumers $\to$ + 3 billion by 2030 \[2\]
  - 90% of this growth from Asia-Pacific region
- Existing methods of electricity supply & usage are unsustainable
- Superconductors offer an opportunity for a step change in power system technology
  - Improved efficiency, lower carbon emissions, increased power-density

\[1\] http://www.eia.gov/forecasts/ieo/world.cfm
\[2\] Professor Sir David King, “The Politics of Climate Change”
Almost all aspects of electric power systems have a superconducting equivalent:

- Transformers, cables, electric machines (motors & generators)

New technologies enabled by superconductors:

- Superconducting magnetic energy storage
- Superconducting fault current limiters
Superconducting Machine Research

- Approx. one third of electricity consumed by industry [1]
  - Approx. two thirds of this consumed by electric motors [2]

- Using superconductors can increase electric / magnetic loading of an electric machine
  - Higher current density $\rightarrow$ increased power density $\rightarrow$ reduced size & weight
  - Lower wire resistance $\rightarrow$ lower losses & higher efficiency / better performance

- Bulk superconductors $>>$ permanent magnets

Superconducting Machine Research

• Five year project funded by Royal Academy of Engineering

• *Engineering Interactions of Magnetic & Superconducting Materials for Electrical Applications*

• Project goals:
  • Investigate AC loss in superconducting coils & loss reduction methods
  • Investigate practical magnetisation of bulk superconductors & optimisation of trapped field
  • Produce a prototype design of a superconducting electric machine with reduced AC loss (higher efficiency), high torque & reduced weight/size
Superconducting Machine Research – Axial Flux

- **Axial flux, trapped flux-type motor**
  - Bulk & wire HTS materials

- **Advantages of axial flux motor**
  - Higher torque/power density & efficiency
  - Compact ‘pancake’ shape
  - Better heat removal
  - Adjustable air gap
  - Multi-stage machines possible
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Mahmoudi et al. 2011 Scientific Research and Essays 6(12) 2525-2549
Project Overview

Engineering Interactions of Magnetic and Superconducting Materials for Electrical Applications

SUPERCONDUCTING ELECTRIC MACHINE DESIGN

Rotor
- Replacement of permanent magnets with bulk superconductors

Modelling
- Bulk models (2D axisymmetric, 3D)
- Shaping/shimming trapped field using magnetic materials
- Pulse magnetization + thermal modelling

Magnetization
- Develop in-situ technique for magnetizing bulk superconductors
- Large scale pulse magnetization within machine

Armature/stator
- Replacement of conventional copper with superconducting wire

Experiment
- Develop transport AC loss measurement rig for superconducting coils

Modelling
- Coil models (2D axisymmetric, 3D)
- Accurately predict critical current + calculate transport AC loss of coils

AC loss reduction using magnetic materials
Engineering Interactions of Magnetic and Superconducting Materials for Electrical Applications

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Stator – AC Loss in Superconducting Coils

- Coils found in many electrical engineering applications
- Many power applications require AC (alternating current, *time-varying*)
- Finite AC loss appears for time-varying current and/or magnetic field
  - Amplified at low temperatures, e.g., $P_{\text{actual}} \approx 20 P_{77 \text{K}}$
- For a superconducting device to be commercially viable
  - Must have improved performance (size, efficiency, cost) over an existing equivalent/conventional device
Stator – Coil Modelling

Implemented in COMSOL Multiphysics

Maxwell’s equations (H formulation) + E-J power law

“Multiphysics” = can be coupled with thermal equations
Coil Modelling – What Do We Want To Know?

- DC properties
  - Maximum allowable current / critical current
- AC properties
  - AC loss
- Magnetic field
  - Peak central field
  - $I$ vs $B_{centre}$
- Effect of critical current density anisotropy $J_c(B, \theta)$
- Effect of inhomogeneities
  - Width, length
- Effect of magnetic materials
  - Magnetic substrates
  - External flux diverters
- Optimisation of coil geometry
Coil Modelling – Why Is It Difficult?

- Why is superconducting modelling difficult?
  - Conventional materials = non-linear permeability, linear resistivity
  - Superconductors = linear permeability, non-linear resistivity
  - Non-linearity is extreme: power law with \( n > 20 \)
  - For standard 3D models, 100,000s elements required in FEM
  - Complicated anisotropy of in-field behaviour \( J_c(B,\theta) \)
Critical Current Density $J_c$

- **Accurate $J_c$ data is crucial for accurate modelling**
  - Can predict coil critical current & AC loss

- **Need engineering equation to represent behaviour**
  - Modified Kim-like models only applicable in some cases

\[
J_c(B, \theta) = J_{c,e}[Bf_e(\theta)]
\]

\[
J_{c,e}(B) = \frac{J_{0e}}{(1 + B/B_{0e})^\beta},
\]

\[
f_e(\theta) = \sqrt{\cos^2 \theta + u_e^2 \sin^2 \theta}.
\]

Souc et al. 2009 *SuST* 22 015006

Pardo, Grilli 2012 *SuST* 25 014008
Test Motor Coils

• Applying these considerations to test motor coils to validate models
  • Triangular & circular pancake coils
• Wound by University of Oxford using SuperPower SCS4050 coated conductor
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Bulk High Temperature Superconductors

- Conventional magnets (NdFeB, SmCo) limited by material properties
  - Magnetisation independent of sample volume
- Bulk HTS trap magnetic flux via macroscopic electrical currents
  - Magnetisation increases with sample volume
- Trapped field given by
  \[ B_{\text{trap}} = A \mu_0 J_c d \]
  [Bean approximation]
Bulk High Temperature Superconductors

- **Record trapped field = 17 T at 29 K**
  - 2 x 26.5 mm YBCO
- **Significant potential at 77 K**
  - $J_c = \text{up to } 5 \times 10^4 \text{ A/cm}^2 \text{ at } 1 \text{ T}$
  - $B_{\text{trap}} \text{ up to } 1 \sim 1.5 \text{ T for YBCO}$
  - $B_{\text{trap}} > 2 \text{ T for (RE)-BCO}$
- **Record trapped field = 3 T at 77 K**
  - 1 x 65 mm GdBBCO
Magnetization of Bulk HTS

- **Three magnetisation techniques:**
  - Field Cooling (FC)
  - Zero Field Cooling (ZFC)
  - Pulse Field Magnetisation (PFM)

- **To trap** $B_{\text{trap}}$, need at least $B_{\text{trap}}$ or higher
  - FC and ZFC require large magnetising coils
  - Impractical for applications/devices
Pulse Field Magnetization

- **PFM technique** = compact, mobile, relatively inexpensive
- **Issues** = $B_{\text{trap}} \,[\text{PFM}] < B_{\text{trap}} \,[\text{FC}], \,[\text{ZFC}]$
  - Temperature rise $\Delta T$ due to rapid movement of magnetic flux
- **Many considerations:**
  - Pulse magnitude, pulse duration, temperature, number of pulses, shape of magnetising coil(s)
- **Record PFM trapped field** = 5.2 T at 29 K (45 mm diameter Gd-BCO) [Fujishiro et al. *Physica C* 2006]
Bulk Modelling

- **Governing equations:**
  - Same $H$ formulation for EM equations
  - PFM needs to include thermal equations
  - $J_c(B,T) + n(B,T)$
- **2D axisymmetric = simple, okay**
  - 3D models required for arrays of bulks (e.g., motor poles)
  - Inhomogeneities play a significant role in magnetisation
Bulk Modelling in 3D – Pulsed Field Magnetisation

• Collaboration with Iwate University, Japan

• Flux dynamics of (RE)BCO bulk superconductors for pulsed field magnetisation
Bulk Modelling In 3D – Pulsed Field Magnetisation

Bulk Modelling in 3D – Pulsed Field Magnetisation

Bulk Modelling in 3D – Pulsed Field Magnetisation

Homogeneous Model
- $B_{app} = 1 \, \text{T}$
- $B_{app} = 3 \, \text{T}$
- $B_{app} = 5 \, \text{T}$

Inhomogeneous Model
- $B_{app} = 1 \, \text{T}$
- $B_{app} = 3 \, \text{T}$
- $B_{app} = 5 \, \text{T}$

$t = 12 \, \text{ms} \, (\text{pulse peak})$

$t = 120 \, \text{ms} \, (\text{pulse end})$
Bulk Modelling in 3D – Pulsed Field Magnetisation

Thank you for listening

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