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XXVII Cycle (D.M. 1061)

Superconductivity in the electric energy conversion at very high efficiency

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Research context and motivation

To fulfil the ambitious targets for reducing emissions and achieve sustainability in transport, industry, as well as energy generation, electric machines' torque density enhancement is paramount.

Electric machines (EMs) equipped with high temperature superconductors (HTS), have the potential to improve electrical machines' performance, since they feature intrinsic near-zero dc resistivity, achieving high current density values at high magnetic field levels.

Superconducting EMs have the potential to achieve:

- **High specific torque**
- **High efficiency**

However, high-temperature superconductors (SCs) also exhibit **non-negligible losses under the AC regime**, increasing the ***quench*** risk in SCs (sudden loss of the superconducting state). Moreover, **cryogenic conditions are a requirement** in SC windings, thus **cooling rotating machines** becomes an overly **complex problem**.

The cooling system can be made static if restricted to the stator windings, hence this research is based on analysing the feasibility and address the design of a superconducting electrical machine with superconducting AC armature windings.

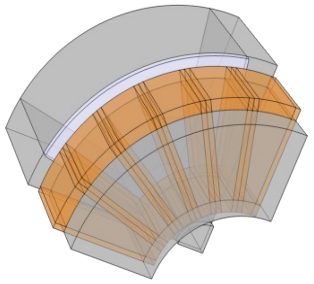
Addressed research questions/problems

Increasing electrical machines' **torque,** requires the enlargement of the machine dimensions (since $T \propto D^2L$).

- Axial flux machines can be realized trough multi-stage structures (i.e., multiple stators and rotors)

Additionally, a consequence of higher current and flux density in the motor is **the increase of iron losses**. **These losses could be partially eliminated** if an axial flux machine were to be built with an **ironless stator.** Given the complex lamination fabrication process this would also be an advantage from the fabrication viewpoint.

Hence the design and modelling of a SC axial flux machine is addressed by stages:



a. Design and simulation of a conventional PM axial flux machine
b. Replacement of copper conductors by superconducting coils (Partially superconducting machine with standard PM on the rotor side)
c. Calibration of machine materials according with measurements in cryogenic conditions (in LN_2 at 77K)
d. Machine topology and geometry adjustment according to field distribution results and loss estimation

Novel contributions

Currently, the research of superconducting electrical machines is mainly focused on:

- Radial flux machines
- Applying superconductors in field excitation coils, carrying DC currents.
- 2D models (time-consuming due to the non-linear superconducting law)
- Submersion based and/or rotating cryocooling methods

From this research, it is expected that simulating and calibrating a **superconductor axial flux machine** will contribute with:

1. Development on the design of axial flux machines with superconductors, and respective opportunities – Partially or fully coreless machines, with possibly higher torque density.
2. Investigation on the applicability of different superconductor types in **AC armature windings,** studies on quench prevention in machine environment and **AC loss mitigation** methods.
3. **Test of different models** to simulate 3D superconducting electrical machines in Finite Element Software

Submitted and published works

- M.Biasion, **I. S. P. Peixoto**, J. F. P. Fernandes, S. Vaschetto, G. Bramerdorferand and A. Cavagnino "Iron Loss Characterization in Laminated Cores at Room and Liquid Nitrogen Temperature" (article accepted for publication in ECCE 2022)
- **I.S.P. Peixoto**, M.Biasion, S.Vaschetto, J.F.P.Fernandes,, P.J.Costa Branco, A.Tenconi and A. Cavagnino, "Superconducting Electrical Machines for Power Dense Energy Conversion" (In progress to be submitted to Journal)

Adopted methodologies

Superconductors can be described by the electromagnetic model:

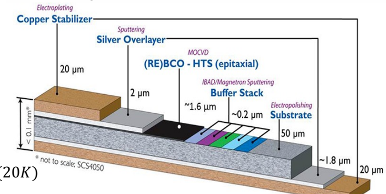
$$\boldsymbol{E} = \frac{E_0}{J_c(B)}\left|\frac{J}{J_c(B)}\right|^{n-1}\mathbf{J}$$

$$J_c(B) = Jc_0\frac{B_0}{B+B_0}$$

where

$$E_0 = 100\mu\text{V/m}$$

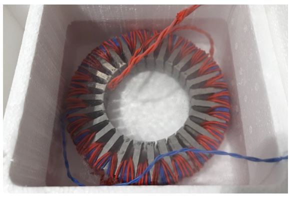
$$J_c^{YBCO} \sim 25\frac{kA}{cm^2}(77K), \qquad J_c^{BSCCO} \sim 15\frac{kA}{cm^2}(20K)$$

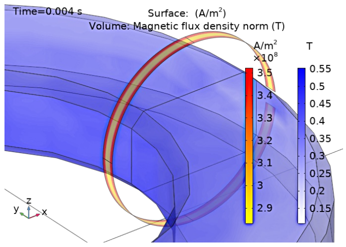


Due to the non-linear superconducting behaviour extensive analysis of finite element method simulations is required in order to address the feasibility of superconducting machines as well as to predict their losses.

Modelling of Superconductors and loss analysis with applied AC current:

a. Modelling superconducting tapes and coils supplied with AC currents in both 2D and 3D with different formulations (e.g., H-A, T-A)
b. Modeling superconducting magnetic circuits supplied in AC, under cryogenic conditions.
c. Benchmark: Calibration of 2D/3D simulations to experimental test on magnetic circuit with REBCO coil

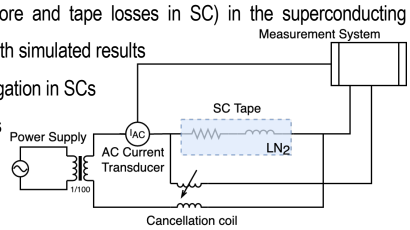




- Iron B-H curve in cryogenic conditions will be measured and used for modeling
- The superconductors' law parameters will be obtained from measurements at different frequencies

Future work

- ❑ Calibration of simulated models with experimental values on wound toroidal ferromagnetic circuit and conventional electric machines stator core
- ❑ Loss separation (iron losses in core and tape losses in SC) in the superconducting magnetic circuit and comparison with simulated results
- ❑ Loss and quench mitigation investigation in SCs
- ❑ Simulation of superconductor tapes in Axial flux machine
- ❑ Study for different SC topologies in similar conditions



Tape circuit for critical current measurement at different frequencies

List of attended classes and Activity in company

Hard skills

- 01DPIRO – Advanced Topics in Energy Storage System and Electric Vehicle Drivetrain Design (7/9/2022, 20h)
- 01DNJRO – Modellazione multi-fisica di sistemi lubrificati (26/7/2022, 20h)
- 01UIJIW – Technological challenges of hypersonic flight (8/7/2022, 20h)
- 03OYCIV – Hybrid propulsion systems (6/7/2022, 15h)
- 01DOBRV – Mathematical-physical theory of electromagnetism (6/6/2022, 15h)
- 02SFURV – Advanced Scientific Programming in Matlab (21/4/2022, 30h)
- 2022 European PhD School in Gaeta, Italy (May 23-25, 2022, 40h)
- 01QORRV – Writing Scientific Papers in English (16/6/2022, 15h)

Soft skills

- 01SWQRV – Responsible research and innovation, the impact on social challenges (24/1/2022, 5h)
- 01UNXRV– Thinking out of the box (19/1/2022, 1h)
- 08IXTRV – Project management (15/1/2022, 5h)
- 01RISRV – Public speaking (15/1/2022, 5h)
- 02LWHRV – Communication (15/1/2022, 5h)
- 01SYBRV – Research integrity (15/1/2022, 5h)
- 01SWPRV– Time management (14/1/2022, 2h)
- Collaboration with Vanzetti Engineering (6 months) : **35% completed**

VANZETTI
CRYOGENIC TECHNOLOGY

Politecnico di Torino
1859

PhD program in
Electrical, Electronics and Communications Engineering