Simulation of Electro-Thermal Transients in Superconducting Accelerator Magnets

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Abstract

Circular accelerators for particle physics require intense magnetic fields to control the trajectories of particle beams. These fields are obtained using electromagnets, wound with fully transposed rectangular cables and cooled down to achieve the superconductive state, allowing the conductors to carry extremely high current densities.

A quench is a sudden transition from the superconducting to the normal conducting state, in which the energy stored in the magnetic field is released as Ohmic losses. Quenches cannot be always avoided and must be considered as a possible operational scenario. Generally, dedicated quench detection and protection systems are in place to avoid overheating of the coil. A careful analysis of the ensuing electro-thermal transient is of great importance for the design of the quench protection systems and safe magnet operation.

We present a coupled electro-thermal 2d model of a superconducting magnet. The model accounts for the non-linear temperature- and field- dependent material properties and for the induced eddy-currents in the superconducting cable, enabling the calculation of quench initiation and propagation.

The construction of the magnet cross-section is realized considering the coil is composed of single turns treated as basic bricks over which material properties and physics laws are homogenized. Since a magnet cross-section usually involves hundreds of turns, as the example shown in Figure 1, the model is automatically built through an external Java® framework that calls the necessary COMSOL® API functions.

The numerical formulation of eddy-currents relates directly the magnetic flux change with the induced effective magnetization. This homogenization technique avoids a resolution down to the conductor filaments, which would require a fine mesh down to the micrometric scale. The formulation has been implemented modifying the set of equations provided by the Ampere's Law node in Magnetic Fields interface. The inter-strand eddy-currents contribution to the equivalent magnetization is shown in Figure 2.

The quench transition function and the material properties are implemented in C then they are compiled as dynamically linked libraries and imported to the model using the

External function node: This implementation has shown to be the most performant. Finally the 100-μm-thick polyamide layer insulating each turn is accounted via the Thin Layer feature that represents its heat capacity, while avoiding an explicit mesh.

We successfully simulated a quench event in a superconducting magnet, and we extracted the coil resistive voltage that is used as input for protection systems. Given the extreme nonlinearities, computational time has been kept at a satisfactory level, thanks to a reduced number of mesh nodes (based on convergence studies) and to the use of dynamically linked libraries that give flexibility and performance beyond the capabilities of lookup tables.

The COMSOL API for use with Java will be deployed to further develop a generalized framework, able to process different coil geometries and magnet designs in an automated way. Structural Mechanics module will be added to future models and coupled with the electro-thermal physics interfaces. Finally the framework will be developed to handle 3d models.

Figures used in the abstract

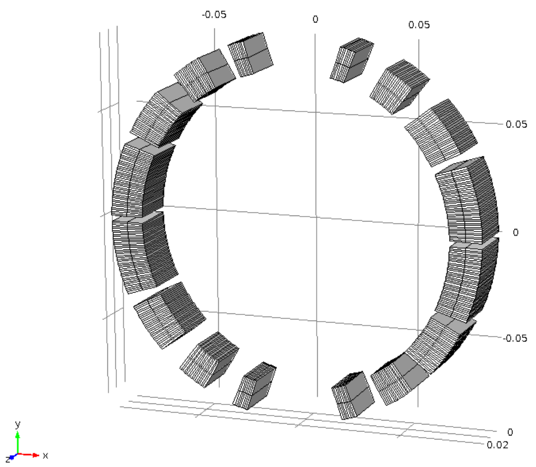

Figure 1: Example of a coil cross-section.

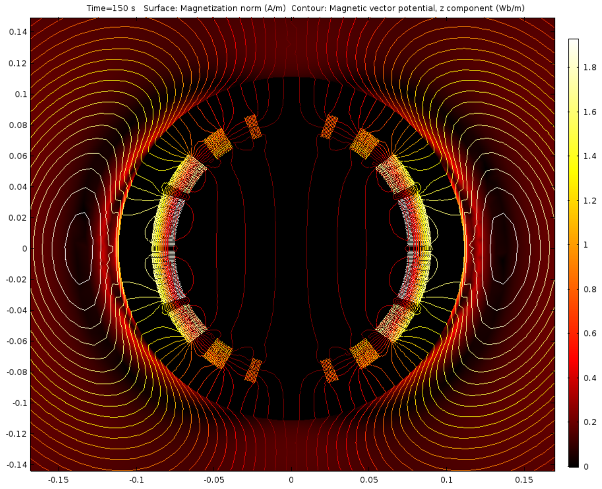

Figure 2: Contribution of Inter-strand eddy-currents to the equivalent magnetization.