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Integrated analysis of quench propagation in a system of magnetically coupled superconducting coils

Claudio Marinucci [a,*], Luca Bottura [b], Marco Calvi [c]

[a] EPFL, CRPP-FT, Villigen PSI, Switzerland
[b] CERN, TE-MSC, Geneva, Switzerland
[c] PSI, Villigen PSI, Switzerland

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ABSTRACT

We demonstrate in this paper how to use direct modeling of heat transfer and circuital equations based on "packaged" simulation tools to produce a model suitable for the study of quench propagation in a system of magnetically coupled solenoids protected without an external dump resistor. Our application example is a system of three, layer-wound and bath-cooled coils, all using a NbTi conductor. The same model can be easily adapted to study coils with different topologies, geometry and conductors. We demonstrate the use of the model by parametric analysis of physical parameters in the system, showing under which conditions a quench-back due to inductive coupling is triggered. The results, and in particular longitudinal and transverse propagation velocities, are consistent with expected analytical scalings. The advantage of the model is that it provides self-consistent results, i.e. based on first principles rather than assumptions on quench propagation, and it gives access to local details that are not intuitive, nor easily measurable.

1. Introduction

The basic process of a quench in superconducting coils is the conversion of stored electromagnetic energy into heat. If the magnet is properly protected, this heat is distributed throughout the magnet winding without damages such as (a) mechanical damage generated by differential expansion of materials due to excessive temperature gradients, (b) deterioration of material properties such as the insulation dielectric strength, or the critical current the superconductor, due to excessive temperature, and (c) electrical stress associated with excessive voltages. Primary goal of a quench analysis is hence the assessment of hot spot temperature T_{max}, peak voltage V_{max} and peak temperature gradients ΔT_{max}, to be limited below properly defined allowable values to avoid any of the above issues.

The issue of protection of superconducting coils is of paramount importance for any type of magnet, from the small solenoids operating at high current densities under adiabatic conditions, to the large coils used for particle accelerators or fusion. Small magnets with little stored energy can be designed so that they are self-protected, and the only action required is to switch off the power converter upon the appearance of a resistive transition. When dealing with large stored energy, the protection of magnetically coupled superconducting coils is generally achieved by subdivision, segmenting the magnetic system in portions that are protected separately and using passive protection expedients such as parallel resistors or diodes to dissipate and by-pass the quenching portion [1,2]. This is common practice for NMR and MRI solenoids, wound using single wires and hence with a large inductance, and segmented in several nested coils. In such systems the interplay of the coupled thermal and circuit transient becomes complex, and an effective design is no trivial matter. In fact, the design and analysis of the quench protection system for a superconducting solenoid is a practical matter that has often been addressed by using simplified models based on analytical estimates for the quench propagation velocities in the longitudinal (tangential) and transverse (axial and radial) directions [3–6]. However, this approach can become cumbersome especially for coil configurations such as segmented magnets or multiple coils with inductive coupling protected without an external dump resistor, i.e. magnets in which the stored electromagnetic energy (converted into heat) is dumped internally and into the coolant. The analytical solutions often require the *a priori* knowledge of the operational regime of the normal zone growth, i.e. if bounded in 1-D, 2-D or 3-D, a condition which depends on known parameters, e.g. aspect ratio of the solenoid (thin vs. thick solenoid), as well as on unknown or less known input data (propagation speed in longitudinal and transverse direction). In many cases the propagation speed is provided as an input parameter by the user. In other cases, analytical

* Corresponding author.
E-mail address: claudio.marinucci@psi.ch (C. Marinucci).

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estimates, or measured values of quench propagation times have been used to achieve accurate simulations [7]. A much preferable approach is to model the quench process self-consistently, i.e. computing the propagation speeds in the three directions, coupled with the circuit equations. A few examples can be found in the collected bibliography, and especially the work of Gavrilin [8,9], Eyssa [10,11] and of one of the authors [12–14]. The work quoted above has demonstrated that direct simulation of the quench process is feasible, but requires coding that is often customized to the specific application (e.g. conductor shape, magnet geometry and topology). More recently, development of direct simulation of quench propagation in magnet systems has received attention in commercial environment codes (see as an example the analyses described in [15–17] that are based on commercial, general-purpose engineering simulation packages).

In this paper we also resort to direct modeling of the heat transfer and circuital equations to produce a model suitable for the above mentioned configurations, producing results based on propagation velocities which are consistent with the physics of the phenomena. Our approach, however, is slightly different from the references quoted earlier, in that we take ad hoc simulation tools developed in the past for the analysis of superconducting magnets [18,19], coupled by a communication protocol that extends their capability to multiple physics domains [20]. The tools are tailored for the simulation of processes in cryogenic and superconducting systems, and are easily adapted to deal with the specific geometry by using built-in features that are user accessible. In this way we avoid the overhead of programming heat and circuit equations, which are a validated part of the standard solvers, of porting a material database, already programmed as a part of the standard libraries, and we focus on the specific features of the system modeled. Our test case is a system of three, layer-wound and bath-cooled coils, all using a NbTi conductor (Fig. 1). The bonus of the approach taken is that the same model can be easily adapted to study coils with different topologies (e.g. pancake winding), geometry (e.g. non-circular shapes) and type of conductors (e.g. force-flow cooled, cable-in-conduit conductor).

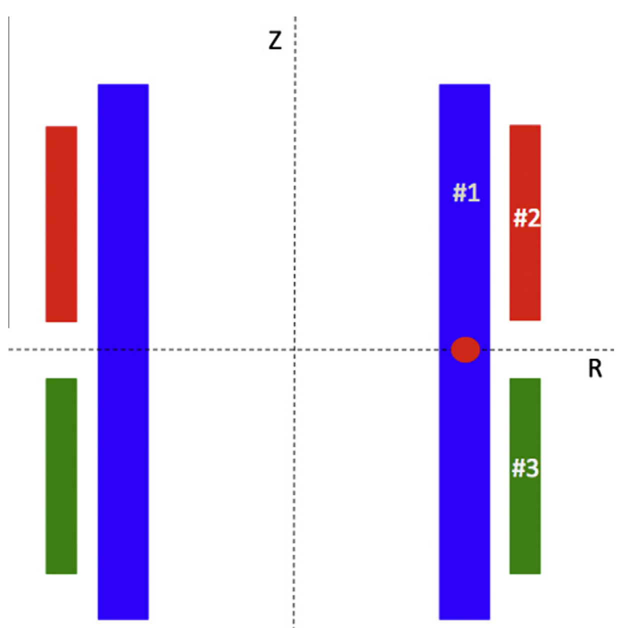

Fig. 1. Schematic (not-to-scale) representation of the test case considered in this paper, i.e. a system of three inductively coupled solenoids consisting of an insert (Coil 1) inside a split pair powered in series (Coil 2 and Coil 3). The axial (vertical) gap between Coil 2 and Coil 3 is approximately equal to the radial thickness of the two coils. Characteristic data for the system is reported in Table 1. The quench is initiated by a heat perturbation applied at half length of Coil 1 ($X = L/2$).

2. Model

2.1. Equations and solution

The problem chosen as a test case for this study can be stated as follows: given a system of magnetically coupled superconducting coils protected without external dump resistor, and further to heat perturbation followed by a quench in one coil, the goal is to compute the evolutions – in time and space – of currents, voltages and temperatures in all coils. We take into account the 3-D longitudinal and transverse heat transfer (turn-to-turn and layer-to-layer) with an equivalent model which combines a 1-D longitudinal continuum model and a simplified 2-D transverse network model, shown schematically in Figs. 2 and 3, to solve the heat exchange among solids and coolant. The method of using equivalent 3-D models by combining 1-D with 2-D models can be a viable alternative to complex full 3-D models [14,21]. The thermal model is coupled to the electrical circuit model which describes the currents in the system of coils.

The building blocks of the model are the CryoSoft™ suite of dedicated codes for the analysis of superconducting coils, i.e. THEA (Thermal, Hydraulic and Electric Analysis of Superconductor Cables) [18], POWER (Electric Network Simulation of Magnetic Systems) [19] and SUPERMAGNET (Multitask Code Manager) [20] which launches the other codes, schedules their communication and terminates execution as appropriate.

Without entering in the details of the models, described in the above references, we report here only the main features. The temperature of the conductor T as a function of time t and of the conductor length x is computed by THEA solving the following 1-D partial differential equation:

$$\sum_i A_i \rho_i C_i \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(\sum_i A_i k_i \frac{\partial T}{\partial x}\right) = \dot{q}\prime + \dot{q}\prime_{Joule} + \sum_{j=1}^{4} P_j + P_{bath} \qquad (1)$$

where we indicate with A_i, ρ_i, C_i and k_i the cross section, density, specific heat and conductivity of the ith constituent of the conductor (e.g. Nb–Ti and Copper), $\dot{q}\prime$ is the external heat perturbation power per unit length, and $\dot{q}\prime_{Joule}$ is the Joule heat power per unit length. In the above form, the equation is the same as the standard implemented in THEA [18]. The additional terms, P_i and P_{bath}, are the power exchange between adjacent conductors, and to the helium bath by which the solenoid is cooled, respectively. They are added to extend the 1-D balance to the simulation of 3-D quench propagation. The transverse power exchange for the generic conductor is approximated as follows (see also Fig. 3):

$$P_{1,2} = (k_{ins}/th_{ins}) R_c (T_{1,2} - T) \qquad (2)$$

$$P_{3,4} = (k_{ins}/th_{ins}) Z_c (T_{3,4} - T) \qquad (3)$$

where $P_{1,2}$ is the turn-to-turn heat conduction and $P_{3,4}$ the layer-to-layer heat conduction power per unit length (W/m), k_{ins} is the thermal conductivity of the insulation, th_{ins} its total thickness, T is the temperature of the generic conductor, $T_{1,2,3,4}$ the temperature of its adjacent conductors, R_c and Z_c the conductor width and height, respectively. The above approximation is good for situations when the temperature gradient across the insulation is in steady state, which is usually the case in compact magnets built with thin insulating layers among conductors.

The heat exchange power per unit length (W/m) with the helium bath is:

$$P_{bath} = hd(T_0 - T) n_{bath} \qquad (4)$$

where h is the heat transfer coefficient to the helium bath, d is the conductor dimension either equal to R_c or Z_c, and n_{bath} is the number of sides which the generic conductor has in contact with the bath (0,