A Numerical Code to Simulate Quenching in Conduction Cooled Superconducting Magnet

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A numerical code (1D+2D) has been developed to simulate quenching in conduction cooled superconducting magnet. The code is formed based on the numerical thermal-physical model to describe an initial hotspot evolution in a practical superconduting coil. The code is in an integrated frame that couples a 1D model and a 2D model, describing the normal zone propagations along the superconductor and among winding turns respectively. Material characteristics of the magnet winding constituents are involved as the basic data to simulate normal zone propagation process. Information such as maximum temperature rise and voltage evolution can be output as the result of code execution. This code is used to perform a quench simulation on the Alpha Magnetic Spectrometer (AMS) superconducting magnet and the simulation results are presented in this paper.

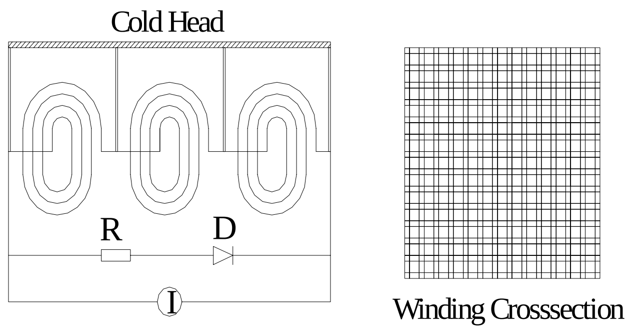
INTRODUCTION

Conduction-cooled superconducting magnet system can be found in many applications[1,2,3] due to their simple operation. In contrast to traditional bath cooling, conduction-cooled superconducting magnets are cooled by cryocooler directly via thermal conduction circuit. In the vacuum environment, the superconducting magnet is operated with no liquid cryogen at all inside the coil windings. During a quench incident, all the energies stored in the magnet have to be dumped into the superconducting windings, resulting in a rapid temperature rise after quench. Severe damages to the magnet should be prevented by appropriate protection measures based on a detailed quench analysis.

A complete description on the physics of normal zone propagation during a quench incident has been summarized by Wilson[4]. Some quench simulation methods to simulate quenching in specified superconducting magnet have been presented by authors[3,5], in which finite difference and finite element method are used. Rough and fast estimation on the hotspot temperature can be obtained by quench integral value and 2D method. Complicated 3D finite element method is preferred but a huge simulation work is needed. Here, we proposed a 1D+2D quench simulation model to evaluate the normal zone propagation in a conduction cooled multi-coil superconducting magnet. As an example, simulation results on a dipole coil in the Alpha Magnetic Spectrometer (AMS) superconducting magnet are presented.

1D+2D SIMULATION MODEL

Superconducting coils are usually wound with a continual superconducting wire. Once a big disturbance happens in the superconducting coil, the initial normal zone will enlarge its size and propagate longitudinally along the superconducting wire. This process can be fairly described by a one dimensional thermal balance model. Meanwhile, the heat will be conducted from the hotspot of the initial normal zone to the adjacent turns/layers. A 2D thermal balance model can be used to define this thermal conduction process. Figure 1 shows the coil circuit and 2D element discretization used in the 1D+2D model.



In the 1D+2D quench simulation model, the coils or winding sections are connected in series and powered by an external power supply. Protection resistor R or diode are connected in parallel with the magnet. Terminals of each coil are anchored to the cold head of cryocooler. Winding cross section of the coil is discretized into rectangular elements. Each conductor is regarded as an element and surrounded by 8 insulation elements.

For the 1D and 2D thermal balance model, the following two differential equations can be used to describe the thermal diffusion process in each discretized element, with boundary conditions of $T_b=T_0$ and adiabatic boundary for equation (1) and (2) respectively.

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + S \tag{1}$$

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) \tag{2}$$

where the temperature and time are denoted by $T(x,y,z,t)$ and t respectively. ρ is material density, C_p is specific heat, k is thermal conductivity and S is source term which is a function of operating current $i(t)$ and normal zone resistance $R(t)$.

When a quench happens, the power supply shuts off immediately and the current will decay through the protection resistor R or diode D. The quenched coil in the magnet has a self inductance of L_q and a mutual inductance M with the rest coils. The total inductance of the magnet is denoted by L_m. The current i(t) and voltage $V(t)$ across the quenched coil can be described by equation (3) and (4) respectively.

$$L_m \frac{di(t)}{dt} + i(t)(R(t) + R) + V_D = 0 \tag{3}$$

$$V(t) = i(t)R(t) + (L_q + M)\frac{di(t)}{dt} \tag{4}$$

1D+2D QUENCH CODE PROGRAMMING

The numerical 1D+2D quench code programming is based on the finite differential method. The 1D and 2D are programmed into two separate subroutines. Each subroutine transfers their results via the main program. Thermal physical properties such as thermal conductivity, specific heat and resistivity, which are functions of temperature, are compiled into data input subroutines.

For the 1D numerical model, the superconducting wire is discretized into N equal elements, with each elements length dx. In a time step dt, the temperature of an arbitrary element i can be expressed as following set of equations, where T_i^0 is the temperature of element i at last dt, j is the current density. ρ_i is the average resistivity of element i at T_i^0. Thermal physical properties such as k, Cp and the density ρ_0 are also averaged on the conductor component ratio.

$$a_i T_{i-1} + b_i T_i + c_i T_{i+1} = R_i \quad (5)$$

$$a_i = -\frac{2k_{i-1}k_i}{dx(k_{i-1}+k_i)} \quad (6)$$

$$c_i = -\frac{2k_{i+1}k_i}{dx(k_{i+1}+k_i)} \quad (7)$$

$$b_i = -(a_i + c_i) + \frac{C_p \rho_0 dx}{dt} \quad (8)$$

$$R_i = \frac{C_p \rho_0 dx}{dt} T_i^0 + j^2 \rho_i dx \quad (9)$$

$$i = 1,2,.......N$$

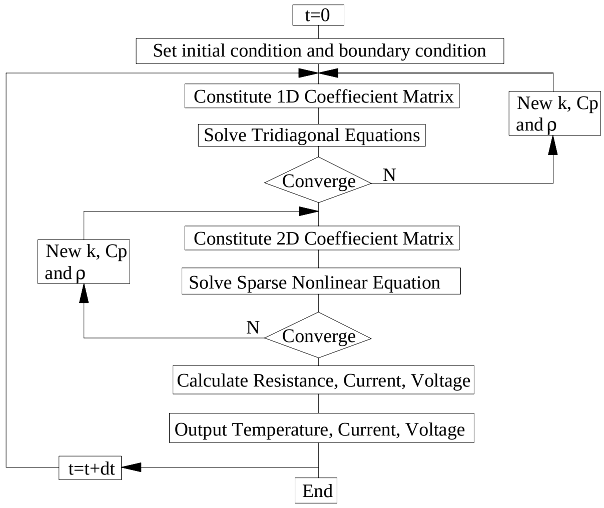


Figure.2 1D+2D Quench Simulation Program Structure

Finally, the 1D numerical model is transformed into a set of nonlinear equations in the tridiagonal system and can be solved by Thomas algorithm for a given time step. And similarly, the 2D numerical model can be also expressed as a set of nonlinear equations and be solved by conjugated gradient method.

The structure of the 1D+2D quench simulation program is presented in Fig.2.

SIMULATION EXAMPLE

The 1D+2D quench simulation program has been performed to analyze the quench process in a dipole coil of AMS02 superconducting magnet. AMS02 superconducting magnet [6] is an assembly of 2 big dipole coils and 12 racetrack coils that are distributed circumferentially to provide a magnetic dipole field. The dipole coil is wound with rectangular aluminum stabilized NbTi/Cu superconducting wire. The cryogenic scheme on the AMS02 superconducting magnet system has been described in detail elsewhere [7]. Parameters of the AMS02 superconducting magnet and the dipole coil are collected in Table 1.

Table 1 Parameters of AMS02 Superconducting Magnet and Dipole Coil

AMS02 Magnet		Dipole Coil	
Total Coils in Assembly	14	Length of Straight Part (cm)	40
Operating Current Io (A)	459	Inner Radius of End Part (cm)	19.5
Peak Magnetic Field (T)	6.59	Winding Cross-section (cm x cm)	8.76 x 14.55
Total Inductance (H)	48.9	Number of Turns	3360
Energy Storage (MJ)	5.15	Conductor Length (m)	8342

The aluminum stabilized NbTi/Cu superconducting wire has a cross section dimension of 2.0×1.546 mm^2. Matrix components are aluminum and copper that each accounts for 84.51%, 7.57% respectively. The RRR of high purity aluminum and copper stabilizer are greater than 1000 and 100 respectively. Thermal physical properties such as thermal conductivity, specific heat and resistivity are estimated based on their purity level.

The quench simulation on the dipole coil is executed based on assumptions that the magnet is closed by a superconducting switch and mutual inductance between the dipole coil and the rest coils in the magnet is excluded in the voltage evolution equation. Simulation results for the temperature rise, current decay and voltage evolution are presented in Fig.3 and Fig.4 respectively.

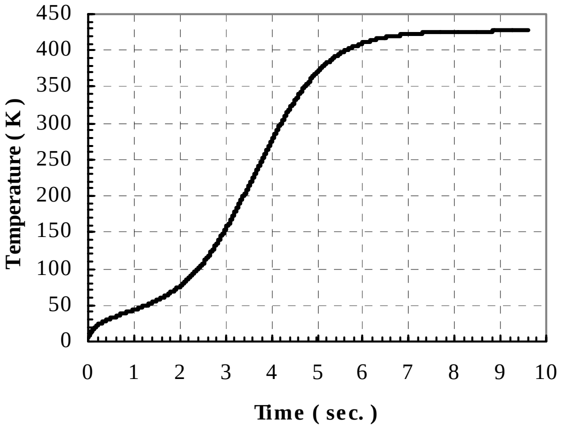


Figure.3 Temperature Rise after Quench

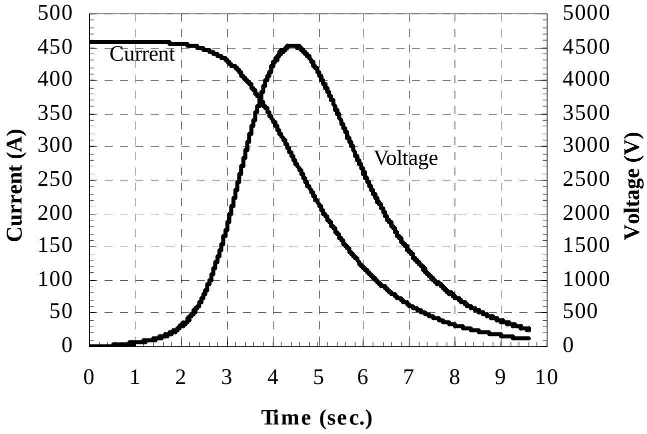


Figure.4 Current Decay and Voltage Evolution

CONCLUSIONS

A numerical quench simulation code 1D+2D is built based on the differential equations describing the one dimensional normal zone propagation along the superconductor and two dimensional thermal diffusion among turns/layers in the coil windings. The nonlinear differential equations are solved iteratively by Thomas algorithm and conjugated gradient method for the 1D and 2D subroutines respectively. During the iteration solving process, the nonlinear thermal physical properties such as thermal conductivity, specific heat and resistivity are updated simultaneously. By coupling the 1D and 2D subroutines through the main program, element temperatures are updated interactively for each time step. Involving the protection circuit, execution of the code can output the maximum element temperature, normal zone resistance, current and voltage at every time step, that are very important data for evaluating the quench protection design.

As an example, the 1D+2D quench simulation code is applied to the safety evaluation of quenching in a dipole coil in AMS02 Superconducting magnet.

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