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# Numerical and experimental study for the quench propagation of a test superconducting magnet

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ABSTRACT

Quench protection design is the key task of the manufacture of a superconducting magnet. The analysis of quench propagation of the superconducting coils is very important for the quench protection design. A numerical model based on the control volume method has been built to simulate the quench propagation. An experiment with five test superconducting coils and an ambient coil was performed to verify the numerical code. The quench protection method of using the heater is proved effective on accelerating the quench propagation by both the simulation and the experiment.



## 1. Introduction

The superconducting magnet technology has now been widely used [1]. A superconducting magnet comprises several superconducting coils and runs under large current. Quench is a thermal-electric coupling phenomenon that may take place in the operation of the superconducting magnet. In an event of quench, the large amount of the electric energy is converted into heat that may do damage to the superconducting coils. If the release of the electric energy is concentrated in a small volume, the local temperature will increase too high and burn the coil. High voltage will be produced in the coils that could break the insulator. High stress could occur inside the winding which may lead to the deterioration of the superconducting wire. Therefore, quench protection is required for the superconducting magnet design. If the energy is distributed into larger volume of the coils, the highest temperature of the magnet will be low and keep the magnet safe. Some commonly used methods of the quench protection is introduced in [2]. For example, the circuit subdivision decreases the voltage and the heater network lowers the hot-spot temperature.

The prediction of the quench propagation is required before the quench protection is applied. Although quench simulation may show good result for a protection design, the experiment for the quench protection design is also needed.

## 2. Numerical model

### 2.1. Heat equation

The quench process is related to the combination of heat conduction and ohmic heating. As quench propagates along longitudinal, radial and axial directions, a three dimensional unsteady heat equation is expressed as:

$$\frac{\partial}{\partial r}\left(k_r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+\frac{\partial}{\partial l}\left(k_l\frac{\partial T}{\partial l}\right)+J^2\rho=\gamma C\frac{\partial T}{\partial t} \tag{1}$$

where $k_r$, $k_z$, $k_l$ are the thermal conductivity along radial, axial and longitudinal directions, $T$ is the temperature, $J$ is the current density, $\rho$ is the electric resistivity, $t$ is the time, and $\gamma C$ is the volumetric heat capacity dependent on $T$.

A three-dimensional control-volume method [3] is employed to solve the problem (1). The domain is divided into a number of control volumes. In the longitudinal direction, the domain is discretized into several grids. Because the start meets the end after the wire is wound for one turn, the last control volume of one turn is the neighbor of the first control volume of the next turn. In the axial direction the size of the control volume is the same as the width of the wire. The outmost part is the flange of the former at two ends of the coil. In the radial direction, the size of the control volume is the same as the thickness of one layer of wire. The innermost part is the bobbin made of alloy or epoxy resin, and the outmost part is several millimeters of insulator (for example, epoxy resin or stainless-steel reinforcement wire). If a heater is employed for the quench protection, the heater becomes the external heat generation source. The heater strip is usually attached to

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the outer diameter of the coil. It has almost the same length as the coil, the width of several centimeters and the thickness of 0.05–0.5 mm [4]. It is wrapped between the coil and the outermost insulator. The boundary condition of the problem is the fixed temperature or the adiabatic condition. The control volume grid layout in only two dimensions of $r$ and $z$ is shown in Fig. 1.

For each control volume numbered by $(i, j, k)$ in Fig. 1, (1) is turned into the discretization equation:

$$\Phi_W + \Phi_E + \Phi_N + \Phi_S + \Phi_T + \Phi_B + G = \gamma C \frac{\Delta T(i,j,k)}{\Delta t} \quad (2)$$

where $W$, $E$, $S$, $N$, $T$ and $B$ denote the six neighbors of the central volume $(i,j,k)$, and $\Phi$ is the heat flux. For the superconducting wire part:

$$\begin{aligned} \Phi_{W,E} &= k_z * \frac{T_{i\mp1,j,k} - T_{i,j,k}}{z\_ins} D_r * \Delta l \\ \Phi_{N,S} &= k_r * \frac{T_{i,j\mp1,k} - T_{i,j,k}}{r\_ins} D_z * \Delta l \\ \Phi_{T,B} &= k_l * \frac{T_{i,j,k\mp1} - T_{i,j,k}}{\Delta l} D_z * D_r \end{aligned} \quad (3)$$

where $D_z$ and $D_r$ are the width and the thickness of the wire. $\Delta l$ is the size of control volume in the longitudinal dimension. $D_r * \Delta l$, $D_z * \Delta l$ and $D_r * D_z$ are the control volume faces. Because the thermal conductivity of the insulator is about three orders less than that of the metal matrix and the superconductor, the conduction between layers is determined by the insulator thermal conductivity $k_r$ and the insulator thickness $r\_ins$. And for the same reason, the conduction between turns is determined by $k_z$ and $z\_ins$, shown in Fig. 1.

The internal heat generation is the ohmic heating in the quenched volume that has the operating current shared with the metal matrix:

$$\begin{aligned} G &= I_0 V = I_0(I_0 - I_c)R_m \\ R_m &= \rho_m \tfrac{\Delta l}{D_r * D_z * (1-\lambda)} \end{aligned} \quad (4)$$

where $G$ is the power of the internal heat generation of every control volume. $I_0$ is the operating current and $V$ is the voltage drop of a quenched volume. $I_c$ is the critical current of the superconducting wire dependent on the local temperature $T$ and magnetic field $B$. $R_m$ and $\rho_m$ are the resistance and electric resistivity of the metal matrix of the wire. $\lambda$ is the fraction of the superconductor contained in the wire.

The external heat generation is the ohmic heating in the heater:

$$\begin{aligned} G_h &= I_h^2 R_h \\ R_h &= \rho_h \tfrac{D_z}{\Delta l * d_h} \end{aligned} \quad (5)$$

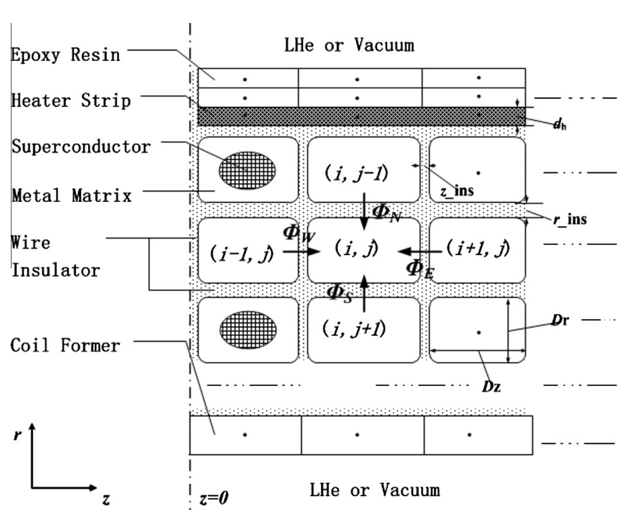


**Fig. 1.** The grid layout of the control volume method (only in the radial $r$ and axial $z$ dimensions).

where $G_h$ is the power of the ohmic heating in every volume of the heater. $I_h$ is the current that flows into the heater strip ($I_h$ could be one of the loop currents in Fig. 2, or the current of an external power supply). $d_h$, $D_z$ and $\Delta l$ are regarded as the thickness, the length and the width of the heater volume. $\rho_h$ and $R_h$ are the heater electric resistivity and the resistance of the heater volume.

The material properties are well considered. The code recalculates the material properties that are dependent on the temperature and magnetic field at each time step.

### 2.2. Circuit model

A typical circuit configuration for a quench protection system is shown in Fig. 2. In the circuit, superconducting coils are connected in series and subdivided in groups. A subdivision resistor with a diode is in parallel with a group of coils to form a loop. The whole circuit is in parallel with a power supply and a dump resistor with a diode. Equations for each loop are:

$$\begin{cases} (I_1 - I_d)R_1 + R_{q1}I_1 + \sum_{j=1}^{n} M_{1,j} \frac{dI_j}{dt} = 0 \\ (I_i - I_d)R_i + R_{qi}I_i + \sum_{j=1}^{n} M_{1,j} \frac{dI_j}{dt} = 0 \\ \cdots \\ (I_n - I_d)R_n + R_{qn}I_n + \sum_{j=1}^{n} M_{1,j} \frac{dI_j}{dt} = 0 \\ \sum_{i=1}^{n} (I_d - I_i)R_i + I_d R_d = 0 \end{cases} \quad (6)$$

where $I_i$ is the current of the coil in loop $i$, $I_d$ is the current of power supply, or of the dump resistor (when the power supply is shut off), $n$ is the number of loops in the circuit, $R_i$ is the resistance of the subdivision resistor in loop $i$, $R_d$ is the resistance of the dump resistor, $M_{i,j}$ is the mutual inductance of $j$ group to $i$ group, and $R_{qi}$ is the sum of resistive zone resistances of the coils in $i$ group. At each time step, after solving the equations above we can obtain the currents of all coils. And then, with the currents we can calculate the magnetic field and the heat generation in each control volume (the quenched wire or the heater).

## 3. Experiment

### 3.1. Coil design

An experiment was performed to verify the simulation code and the quench protection method. A small test superconducting magnet was built. It consists of five superconducting test coils and an existing ambient coil to yield a high magnetic field on the test coils. The self-inductance is 1.1 H of the test coils and 5.5 H of the

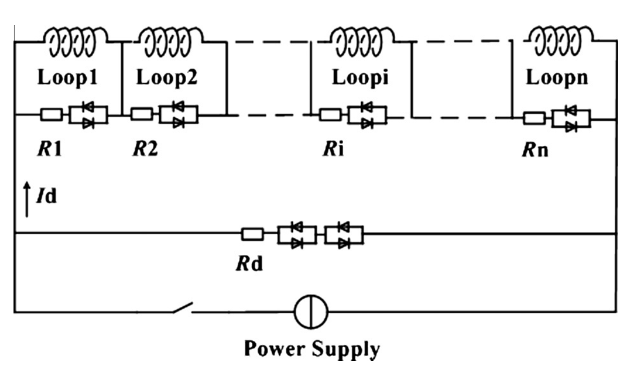


**Fig. 2.** A typical quench protection circuit configuration.