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# Quench characteristics in the multi-sectioned superconducting magnet impregnated with epoxy resin

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**Abstract**

A two-dimensional model is proposed to analyze the thermal and electrical behavior of quench in a multi-sectioned superconducting magnet impregnated with epoxy resin. In the simulation, the effect of AC losses due to the field variation is included. The three-coil system and NMR superconducting magnet system are studied. The temporal variations of current, voltage and hot-spot temperature rise of magnet system are analyzed. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Multi-sectioned magnet; Quench simulation; NMR magnet; AC losses

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## 1. Introduction

The superconducting magnets for NMR or MRI are fabricated with closely compacted winding and impregnated with epoxy resin. These magnets consist of multi-sectioned superconducting coils in order to increase the center field and the homogeneity of the field. Quench protection is an important aspect in the design and fabrication of magnets because quench in the magnet can burn out the conductor, and the turn-to-turn voltages developed may damage the insulation. When a disturbance occurs in the magnet, the temperature of the hot-spot increases, and the size of normal zone grows to all directions of the magnet. Some simulation codes have been developed to study the quench process [1–3]. Most of the codes are related to a sample approximate method to calculate the normal zone propagation velocity and the hot-spot temperature rise [4,5]. The shortcoming of the methods is that the temperature and normal zone propagation velocity predicted in the coil are higher than their actual values. Therefore, the induced quench time in the coil is earlier than the actual time. In this paper, a computer code has been developed on the basis of a two-dimensional model. The effect of AC losses is included due to the fast current transfer between coils.

## 2. Numerical model of electrical and thermal characteristics

If a disturbance is enough to raise the temperature of the superconductor up to its current sharing temperature, the Joule heat is generated in

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the coil. The thermal diffusion along the conductor is much faster than that along turn-to-turn because of high thermal conductivity of copper matrix. Here, some basic assumptions are taken into account in the mathematical model. (1) The magnet is in the adiabatic condition. Because of the relatively low thermal conductivity of the winding, almost all of the energy stored in the magnet is dissipated in the winding and protection resistor. (2) The magnet impregnated with epoxy resin is treated as an anisotropic continuum medium model with thermal conductivity $k_z$ along the axial direction and $k_r$ along radial direction of the magnet. (3) The normal zone propagation is dominated by turn-to-turn transverse thermal diffusion. Since the normal zone propagation along the length of conductor is very rapid, each turn can be considered to become normal at once when the normal zone boundary reaches it [6]. Therefore, the basic thermal diffusion equation is

$$\gamma C(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk_r(T)\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_z(T)\frac{\partial T}{\partial z}\right) + Q_j + Q_{\mathrm{ac}} + Q_{\mathrm{d}} \qquad (1)$$

where $t$ and $x$ are the time and the space coordinate, respectively. $T$ is the temperature, $Q_{\mathrm{d}}$ and $Q_{\mathrm{ac}}$ are the external disturbance and power densities of AC losses. $\gamma C$ is the average heat capacity of magnet.

The Joule heat, filament coupling and hysteresis losses can heat up the winding. The expression of the filament coupling losses, $Q_{\mathrm{cp}}$, is given by the following equation:

$$Q_{\mathrm{cp}} = \left(\frac{R_{\mathrm{f}}}{R_{\mathrm{w}}}\right)^2\left(\frac{l_{\mathrm{c}}}{2\pi}\frac{\mathrm{d}B_i}{\mathrm{d}t}\right)^2\left(\frac{1}{\rho_{\mathrm{t}}} + \frac{1}{\rho_{\mathrm{w}}}\frac{R_{\mathrm{w}}^2 - R_{\mathrm{f}}^2}{R_{\mathrm{w}}^2 + R_{\mathrm{f}}^2}\right) \times (1-\lambda_{\mathrm{w}})\left(1 - \exp(l_{\mathrm{p}}/l_{\mathrm{c}})^2\right) \qquad (2)$$

where $\lambda_{\mathrm{w}}$ is the ratio of epoxy resin in the winding, and $B_i$ is the field in the strands. $\rho_{\mathrm{t}}$ and $\rho_{\mathrm{m}}$ represent the transverse and matrix resistivity, respectively. $R_{\mathrm{w}}$ and $R_{\mathrm{f}}$ denote the radius of the strand and the superconducting filament zone, respectively. $l_{\mathrm{p}}$ and $l_{\mathrm{c}}$ are the twist pitch and critical twist pitch of superconducting filament, respectively. If $B$ and $\tau$ are the external field and the time constant of strands, respectively, the field variation in superconducting strand is $\mathrm{d}B_i/\mathrm{d}t = \mathrm{d}B/\mathrm{d}t - (B_i(0) - (B(0) - (\mathrm{d}B/\mathrm{d}t)\tau))\mathrm{e}^{-t/\tau}$. The hysteresis losses, $Q_{\mathrm{hy}}$, are determined by

$$Q_{\mathrm{hy}} = \frac{4}{3\pi}\frac{1-\lambda_{\mathrm{w}}}{1+f}d_{\mathrm{eff}}j_{\mathrm{c}}\left(\frac{\mathrm{d}B}{\mathrm{d}t}\right)\left(1 + \left(\frac{j}{j_{\mathrm{c}}}\right)^2\right) \qquad (3)$$

where $d_{\mathrm{eff}}$ denotes the effective filament diameter, $f$ is the copper to superconductor ratio in strands, and $j_{\mathrm{c}}$ is the critical current density. From Eqs. (2) and (3), the rapid variation of field can produce high AC losses to generate quench of the magnet system. In order to minimize the damage caused by a quench and to control the current decaying rate, each coil is connected with a shunt resistor. In a multi-sectioned magnet system, the basic equation of the circuit network can be determined by

$$\sum_{i,j=1}^{n} M_{i,j}\frac{\mathrm{d}I_i}{\mathrm{d}t} + I_i(R_i + R_{\mathrm{d}i}) = I_0 R_{\mathrm{d}i} \qquad (4)$$

where $I_0$ is the operating current, $R_{\mathrm{d}i}$ is the shunt resistance, $I_i$ is the current in $i$th coil, and $M_{ij}$ is the mutual inductance. $R_i$ is the time-dependent normal zone resistance in $i$th coil.

The field can be calculated by a numerical integration method. The mutual and self-inductance of the magnet system are calculated by the code SMIND. Eq. (1) can be solved by the Crank–Nicholson central difference scheme with unconditionally stable. The time step size $\Delta t$ for the thermal problem and the circuit equation is identical, thus, $\Delta t$ is much shorter than any time constant presented in the circuit.

## 3. Quench simulation results and discussion

The code is applied to a three-sectioned magnet system. The parameters of the magnet system are listed in Table 1. Each coil is connected to an external protection resistor, $R_{\mathrm{d}}$ of 0.05 Ω. The initial current of the magnet system is 100 A. A quench is initiated in the highest field region of SM-1 coil. In the simulation, the power supply is a constant current source until the terminal voltage reaches a specified limit value. After that, it is considered to be a constant voltage source. Fig. 1 shows the

Table 1
Parameters of three-coil system

| | Inner radius (mm) | Outer radius (mm) | Height (mm) | Turn number | Filament diameter (μm) |
|---|---|---|---|---|---|
| SM-1 | 48 | 66 | 100 | 2875 | 40 |
| SM-2 | 70 | 80 | 100 | 2083 | 40 |
| SM-3 | 82 | 90 | 100 | 2500 | 40 |

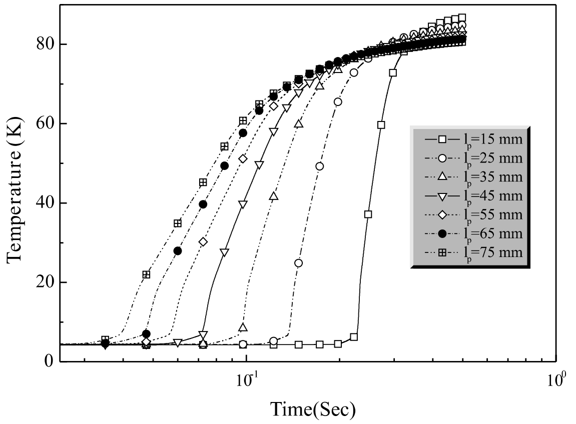

Fig. 1. Profiles of temperature with respect to time in the three-coil system for the twist pitch lengths of 15–75 mm.

profiles of the temperature with respect to time in SM-3 during the quench in SM-1 for the twist pitch lengths of 15–75 mm. The large twist pitch length generates the high AC losses in the SM-3. It results in fast quench in the SM-3, such as, SM-3 starts to quench at about 0.04 s for twist pitch length of 75 mm. But, at the same operating condition, the SM-3 remains in the superconducting state until about 0.22 s for the twist pitch length of 15 mm, and then the temperature of hot spot increases due to Joule heat generated by the induced current in the SM-3 over than its critical current. It is noticed that the beginning of quench time gradually decreases with the increment of twist pitch length. It demonstrates that the heating effect of the inter-filament coupling losses in superconducting strand can generate premature quench between thermally insolated coils. Figs. 2 and 3 show the current and voltage with respect to time in SM-3 for various twist pitch lengths of filament, respectively. The large twist pitch length produces

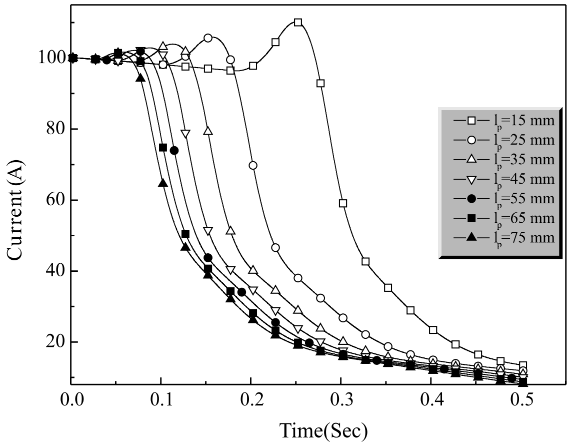

Fig. 2. Current traces versus time in the three-coil system for the twist pitch lengths of 15–75 mm.

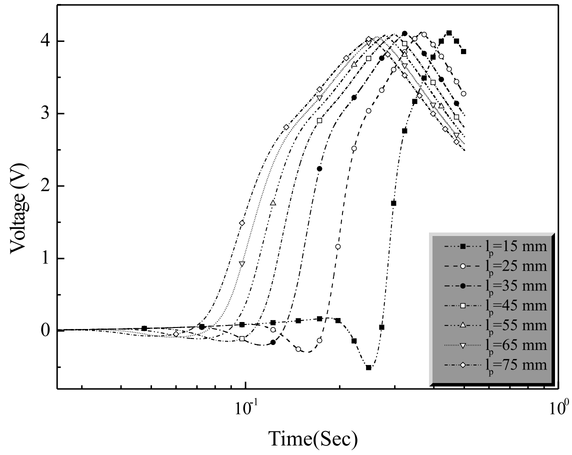

Fig. 3. Voltage traces with respect to time in the three-coil system for the twist pitch lengths of 15–75 mm.

the current fast decayed and the voltage slowly increased. The influence of twist pitch in strand tends to flat with increasing twist pitch lengths from 15 to 75 mm.

The quench properties of a 600 MHz NMR superconducting magnet system are studied by the code. In the simulation, the NbTi coils (nos. 4–8) are taken into account with $Nb_3Sn$ coils removed (nos. 1–3). The parameters of the magnet are listed in Table 2 and the configuration of NMR NbTi coils is shown in Fig. 4. The superconducting strand with the twist pitch length of 28.5 mm and

Table 2
Parameters of NMR superconducting magnet system

| | Inner diameter (mm) | Outer diameter (mm) | Height (mm) | Turn number | $R_{\mathrm{di}}$ (Ω) |
|---|---|---|---|---|---|
| Coil-4 | 177.16 | 210.74 | 517 | 6034 | 0.288 |
| Coil-5 | 214.3 | 253.9 | 517 | 8442 | 0.324 |
| Coil-6 | 268.04 | 316.44 | 127 | 2552 | 0.125 |
| Coil-7 | 268.04 | 309.84 | 20 | 342 | 0.032 |
| Coil-8 | 268.04 | 316.44 | 127 | 2552 | 0.125 |

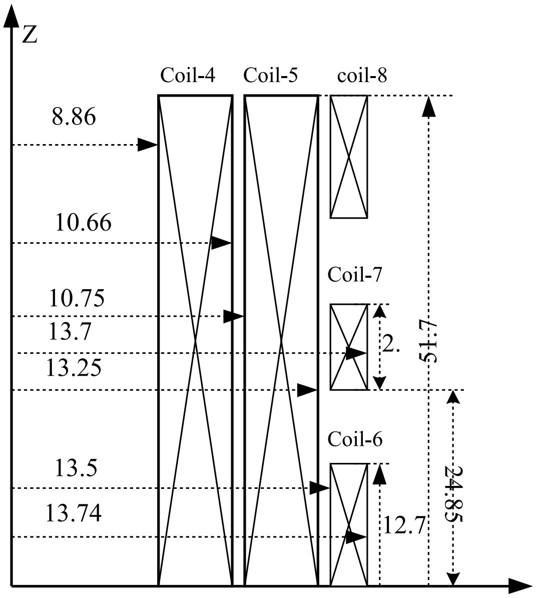

Fig. 4. Configuration of NbTi superconducting coil in the 600 MHz NMR system (unit: cm).

the filament diameter of 50 μm is used. Each coil of NbTi is shunting by an external protection resistor. The power supply is connected with the magnet system. The initial normal zone is located at the coil-4. Fig. 5 shows the simulation results of currents versus time after the coil-4 in the magnet system quenched prematurely at 150 A. The current of coil-4 is decaying with time due to quench. On the other hand, the currents of the other coils are increasing at the beginning because they are still in the superconducting state. When the currents are over their critical currents at about 1.5 s for the coil-5, about 2.2 s for the coil-6 and 8, and about 1.9 s for coil-7, the currents begin to decay.

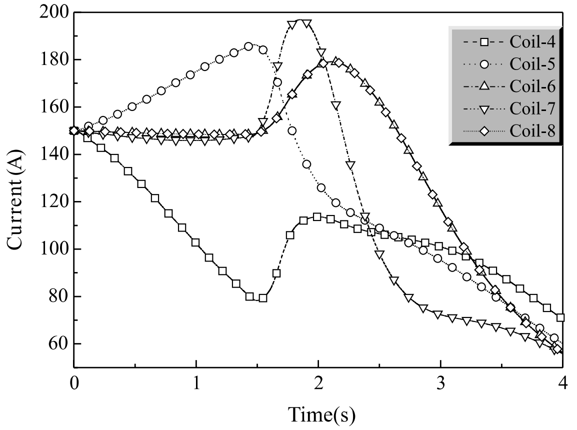

Fig. 5. Current traces of the coils 4–8 for the initial operating current of 150 A.

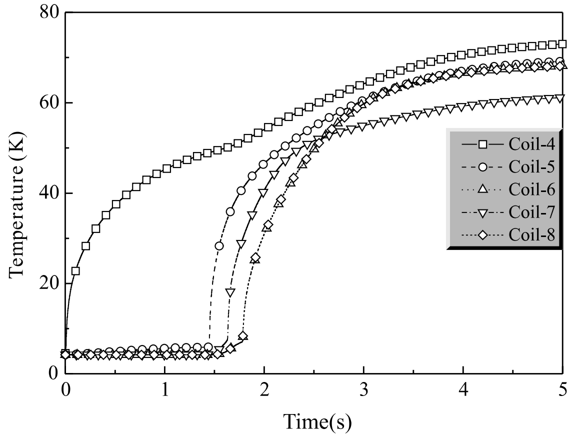

Fig. 6. Profiles of temperature versus time in the coils 4–8 for the initial operating current of 150 A.

The hot-spot temperature traces of the magnet system are shown in Fig. 6. The hot-spot temperature in the coil-4 increases rapidly at first 1 s, and then it tends to flat due to the current coupling between coils. The maximum temperature rise in the coil-4 is lower than 75 K. From Fig. 6, the AC loss plays an important role in quench of the other coils. When the AC losses are considered, the temperatures of coils in superconducting state are increased. The coil whose temperature is lower than its current sharing temperature can be warmed up by two mechanisms, i.e. heat conduction from neighboring conductors and the AC

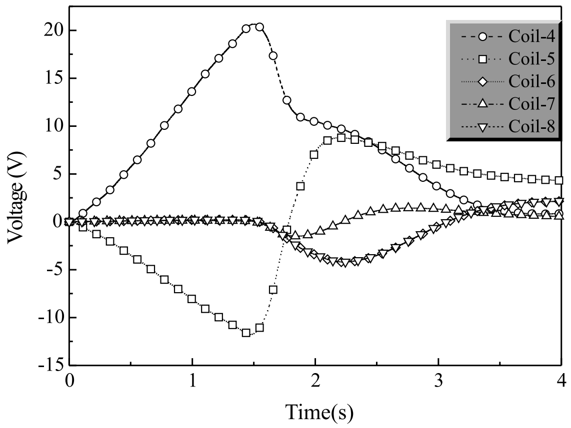

Fig. 7. Voltage traces across coils 4–8 for the initial operating current of 150 A.

losses. The heat conduction depends on the thermal conductivity of turn-to-turn in winding. The AC losses depend on the twist pitch length, effective filament diameter and changing rate of the field. The profiles of voltages in coils are shown in Fig. 7. The maximum voltage of 20.7 V appears in the coil-4 at about 1.5 s.

The temperature distribution of magnet system during quench process of the magnet operated at 150 A was simulated from 1 to 4 s of time. Fig. 8 shows the profiles of temperature with respect to the space. The coil-4 is in partially normal state and the other coils are in fully superconducting state at time $t = 1$ s, and then coils 4, 5 and 7 are in fully normal and coils 6 and 8 are in partially superconducting state at time $t = 2$ s. It shows that the average temperature method to calculate the temperature of coils is not suitable because the temperature difference in the same coil may be over about 20 K.

## 4. Conclusion

A numerical simulation code has been developed and applied to predict the quench behavior in the three-sectioned superconducting magnet system and NMR system. The code can predict the time-dependent magnet currents, induced voltages, and temperature of quench in the superconducting magnet system. The results indicated that the AC losses from the field variation in the coils are an important heat source term to trigger the quench of the thermally isolated superconducting coils. The average temperature method calculates that the temperature in the coil is higher than its actual value.

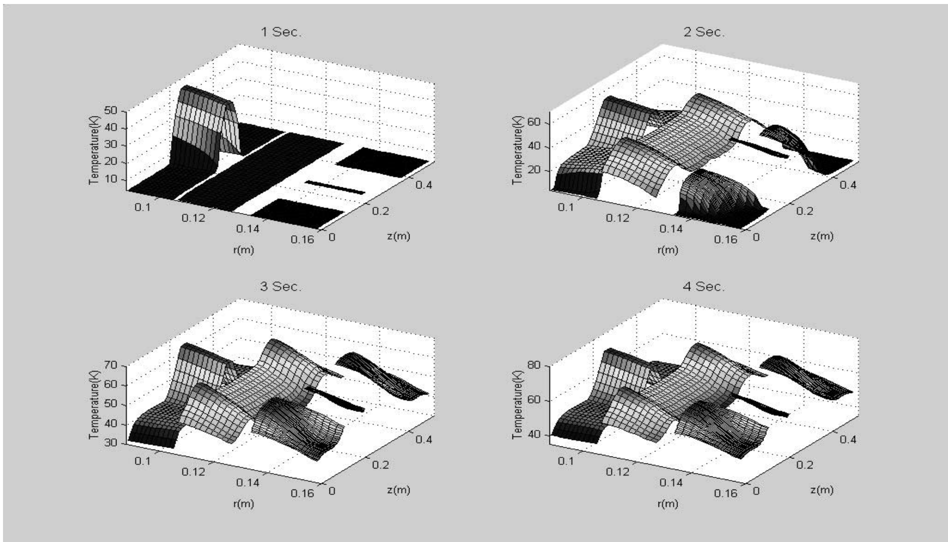

Fig. 8. Temperature distribution in space for the NMR magnets system during quench at the initial current of 150 A. (Coil No. is the same as Fig. 4.)

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