Quench Simulation for 9.4 T MRI Superconducting Magnet

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Abstract. The 9.4 T MRI superconducting magnet is being fabricated. A quench simulation code based on anisotropic continuum model has been developed for the quench protection design. The quench behavior of the magnet is studied by means of the code. A commercial software based on finite element method is also applied to the quench simulation of the magnet. The calculation results of the two numerical methods have been compared and analyzed.

1. Introduction to the 9.4 T MRI superconducting magnet
A 9.4 T whole-body MRI superconducting magnet composed of 5 main coils (named as A, B, C, D, and E), and 4 compensating coils (named as F1, F2, G1, and G2) is being fabricated, shown in figure 1. The coils are wound with Wire-In-Channel NbTi/Cu conductors with different cross-section sizes, Cu/SC ratios and critical currents.

All of the coils are powered in series with the operating current of 212.5 A. The inductance of the magnet is about 6000 H, and the stored energy is about 134 MJ. The magnet produces a central magnetic field of 9.4 T. The highest magnetic field of about 9.5 T locates inside the innermost coil A. Because of the high magnetic field inside the coils, the temperature margins (ΔT=Tcs−T0) of the coils are very low. Some design parameters and operating conditions of the coils are listed in reference [1].

2. Quench protection scheme of the 9.4 T superconducting magnet
The passive quench protection method is adopted. The circuit subdivision and heater network are employed in the quench protection scheme. In order to restrict the coil voltages during the quench event, each main coil is subdivided into 2 sections and the 4 compensating coils are combined into one section. Each section is in parallel with a back-to-back diode and a shunt resistor. In order to accelerate the quench propagation and lower the temperature rise of the coil, the quench heaters are...
used, which are attached on the coil outer surfaces. The heaters are also used as the shunt resistors of the circuit sections and are powered by the currents split from the circuit sections during quench.

The circuit configuration and the heater network are illustrated in figure 2. The working process of the heater network is that if a coil initiates to quench, the current split from the section of the coil will power the heaters of H11-14, trigger the coils F1, F2, G1, and G2 to quench, and then the current split from the section of the 4 coils will power all other heaters, triggering the rest of coils to quench. The detailed quench protection design is introduced in [2].

![Figure 2. Configuration of the protection circuit and the heater network of the 9.4 T magnet](image)

3. A quench simulation code based on the anisotropic continuum model

A quench simulation code has been developed in our laboratory for the quench protection design [3][4]. The anisotropic continuum model (ACM) is adopted for the prediction of the quench resistances, currents, and voltages of the solenoid superconducting coils. When a quench initiates from a spot in a coil, the normal zone propagates along longitudinal, radial and axial directions. Because the quench propagation velocities along the three directions are not the same, the quench evolution front is assumed to be an ellipsoidal envelope [3]. The ellipsoid is described in cylindrical coordinate as:

\[
\frac{(r - r_0)^2}{R_0 + \sum \nu_r(t) \delta t} + \frac{(z - z_0)^2}{Z_0 + \sum \nu_z(t) \delta t} + \frac{\phi^2}{\Phi_0 + \sum \nu_l(t) \delta t} = 1
\]

where \(r_0, z_0\) are the radial and axial coordinates of the spot where the quench initiates. \(\nu_r, \nu_z, \nu_l\) are the radial, axial and longitudinal quench propagation velocities. \(R_0, Z_0, \Phi_0\) are the radial, axial and longitudinal dimensions of the original ellipse, which are usually triggered by heaters.

The volume of the normal zone is the volume of the ellipse that is confined inside the coil. With the ellipsoidal normal zone volume, the quench resistance of the coil is calculated, and then the coil current can be obtained at each time step. The wire material properties and critical properties dependent on the local time-varying magnetic field and temperature are considered.

The 9.4 T magnet comprises multiple coils, which are electromagnetic coupled. The quench behavior with respects to the coil currents and voltages is closely related to the quench sequences of the coils. The quench is started by the heater triggering (except the coil that initiates to quench). Therefore, the calculation of the times that the heaters trigger the coils to quench is required.

Since the ACM could not predict the quench starting times of the coils, the 2D control volume method (CVM) is adopted. It models the heat conduction between the coils and the heaters [4], shown in figure 3. The heat generation of the problem is the ohmic heating in the heater. It is assumed that when the temperature of a control volume in a coil rises above its current sharing temperature \(T_{cs}\), the quench of the coil will be triggered by the heater.
In order to increase the computational speed of the simulation for many attempts of quench protection designs, the CVM will be altered to the ACM when a coil is triggered to quench by heater. By means of the code, the quench simulation for the 9.4 T magnet with the above quench protection scheme is conducted. It is assumed that the quench event initiate in coil A. The calculation result shows that the highest temperature rise is below 100 K, the highest coil voltage is restricted below 400 V and the strongest hoop stress is limited below 150 MPa among all coils. It is concluded that the safety of the magnet is guaranteed during quench. The details are shown below.

4. Quench simulation comparison between a commercial software and the ACM code

A commercial software ‘Vector Fields Opera-Quench’ is applied to the quench simulation of the 9.4 T superconducting magnet. The software is based on the finite element method (FEM), and combines the 3D magnetic field calculation into the 3D thermal calculation [5]. The software employs the same geometric parameters, circuit configuration, and material properties as those inputted into the code discussed above.

The simulation results of coil currents, voltages and temperature rises by both the FEM and ACM are shown in figure 4 to figure 6. Results by the two models show good agreement with respect to the shape of curve, the peak value, and the time of decay to a low level (figure 4, 5). In figure 6 the coil temperature rises by the ACM are higher than those by the FEM. This may be due to the adiabatic assumption in the ACM. Besides, the computation time for the FEM is near 16 hours, while the time for the code developed by us is about half an hour, with the same computer. The ACM code is preferable for the parametric optimization (such as circuit shunt resistance, heater width, etc.) of the quench protection design, and the FEM could be supplementary verification of the optimized design.

**Figure 3.** The 2D grid of the CVM for the problem of heat conduction between heater and coil

**Figure 4 (a).** Coil currents by the ACM model.

**Figure 4 (b).** Coil currents by the FEM model.
5. Conclusion
A quench simulation code based on the ACM has been developed by us and applied to the 9.4 T MRI superconducting magnet. The simulation results show that the temperature rise, the voltage, and the hoop stress of each coil are within the safety level during quench. The FEM is also employed to simulate the quench behaviour of the magnet. The calculation results of the FEM shows good agreement with the ACM, but the computational speed of the FEM is much slower than the ACM. Besides, the ACM code has been verified by experiments. The details are presented in [6].

References
[1] Wang Q et al 2012 A superconducting magnet system for whole-body metabolism imaging IEEE Trans. Appl. Supercond. 22 4400905
[2] Li Y et al 2014 A Passive Quench Protection Design for the 9.4 T MRI Superconducting Magnet IEEE Trans. Appl. Supercond. 24 4401605
[3] Wilson M 1983 Superconducting Magnet (OXFORD: Oxford University Press)
[4] Li Y et al 2012 Quench protection design of a 1.5 T superconducting MRI magnet IEEE Trans. Appl. Supercond. 22 4703604
[5] Aird G J et al 2006 Coupled transient thermal and electromagnetic finite element simulation of quench in superconducting magnets Proceedings of ICAP (Chamonix France) pp 70–73
[6] Li Y et al 2013 Experimental study for the quench protection system of the 9.4-T whole-body MRI superconducting magnet IEEE Trans. Appl. Supercond. 23 4401309