Influence of Protection Circuit on Quench Characteristics for Clinical MRI Superconducting Magnets

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Introduction

MRI technology utilizes highly sophisticated superconducting (SC) magnet technology. During the prototyping of the SC MRI magnet, quenching (*i.e.*, catastrophic helium evaporation and complete loss of liquid helium) can often occur. Therefore, a reliable quench analysis is very important for the development of SC- MRI magnets. However, it is difficult to accurately model quench characteristics due to the complicity of the involved physics. For example, considerable challenges are faced [1] in modeling the nonlinear behavior of diodes, which are widely used in quench protection systems. In this work, an advanced quench model of the SC magnet- OPERA-3D/QUENCH (Vector Fields, Oxford) module was used to comprehensively analyze the quench performances of two types of superconducting magnets which include symmetric [2] and asymmetric magnets [3]. The model strictly couples the electromagnetic and thermal properties of the system and the quench propagation is characterized in detail with typical quench protection circuitries.

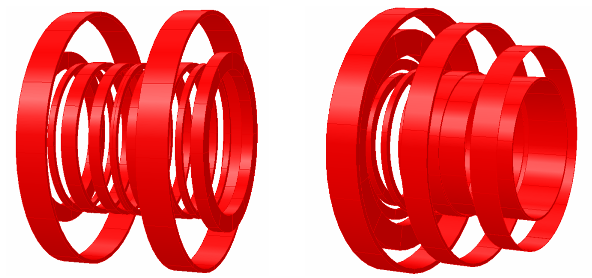

Fig. 1 1T superconducting magnet models.
(a): symmetric configuration [2]; (b): asymmetric configuration [3].

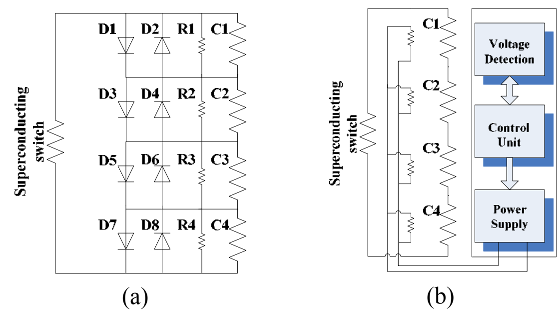

Fig. 2 Schematic diagram of two quench protection systems.
(a): the passive system; (b): the active system.

Methodology

Quench Model and protection circuits: In this work, two structurally different SC magnets were considered, as shown in Fig. 1 which are the perspective models of example symmetric [2] and asymmetric magnets [3]. To ensure safe operation of these magnets, conventional quench protection systems (passive and active types [1]) were employed, as illustrated in Fig. 2. In the passive protection system, each coil was shunted by a quench heater R in parallel with reversely connected diodes. Through this electrical and thermal connection, if one coil block quenches, the voltage developed in that coil will engage the heaters imbedded in other coils and then propagate into normal zones thus distributing the magnetic energy into all of the coil blocks. Instead of internal loops, an external heating circuit was recruited in the active protection system. In such a system, the control unit is programmed to receive the voltage signal from a detection circuit and determine whether quench has occurred by a comparison between monitored voltage values and a preset threshold. In the case that a quench signal has been measured, the heating system will be immediately activated to quench all the coils in the magnet system. A table function was adopted to express the temperature and magnetic field dependency of the current density of the nonlinear NbTi material. An initial temperature of 4.2K was imposed over the entire geometry.

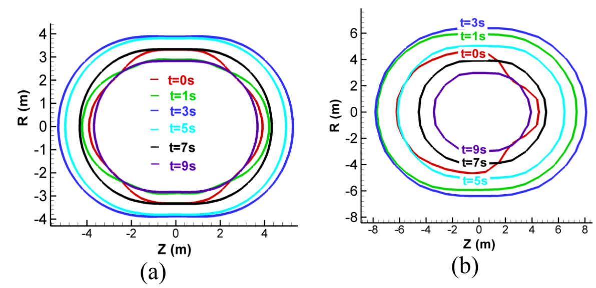

Fig. 3 The 5-gauss contours during the quench simulation with passive protection system: (a): symmetric configuration; (b): asymmetric configuration.

Results and discussion: The investigations can be summarized as follows: (1) from the recorded maximum temperature during quench (see table 1), we can see that both passive and active protection systems are able to quickly deposit the energy over the entire magnet to ensure that the maximum temperature is maintained below the hazardous region; (2) the fringe field was computed according to transient currents during quench. As currents in the coil blocks are identical for the active protection system, the shapes of 5-Gauss contour uniformly shrink during quench. The stray fields meet the safety requirements for a normal operation, no adverse effects after quench were found. Fig. 3 corresponds to those 5-Gauss contours with a passive protection system. Initially the 5-Gauss contours grew to its largest size and then converged into smaller space. Compared to those of active protection system, which restrains the stray field by forcing currents drop together, the 5-Gauss contours reached larger boundaries: 5 meters for the symmetric magnets and 8 meters (in the axial direction) for the asymmetric magnet. This raised safety concerns for the patients and surrounding electrical apparatus. Fortunately, the asynchronous coil currents in symmetric magnets didn't significantly distort the 5-Gauss contours and the distribution of stray field was within the tolerance; (3) with the active protection system shown in Fig.2(b), the currents in the coil blocks dropped from their full-levels to zeros within 4~6 seconds (see Fig.4). Due to the presence of reversely connected diodes in the passive protection system, the quench voltage of superconducting coils will be clamped at one volt of diode (forward voltage), which avoids the damage to the insulation due to excessive high voltage. In contrast, relatively higher voltages were produced in the active protection system, which is not suitable for the protection of the asymmetric magnets.

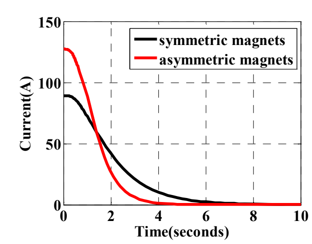

Fig.4 The Coil current changes during the quench simulation with active protection system

Table 1 The Maximum temperatures

Maximum temperature	Passive protection	Active protection
Symmetric magnets	80K	78K
Asymmetric magnets	120K	105K

Conclusion

Understanding the quenching process in SC materials is of particular importance for the SC MRI magnet designs. The simulations demonstrated the effects of topologically different quench protection systems, which are useful for the design and optimization of quench protection systems to ensure safe operations for both conventional and dedicated systems. The passive protection circuit is the most preferable protection system for symmetric magnets; it is desirable to develop a dedicated protection system for asymmetric magnets and this is under development.

Reference

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