Simulation of Pulse Quench Propagation in Superconducting Magnets for the Next Generation Compact Fusion Energy Experimental Device

Abstract: The poloidal field (PF) coils of a fully superconducting tokamak fusion device are primarily used for plasma initiation, shaping, and equilibrium maintenance. These coils must provide sufficiently large alternating currents and extremely fast varying magnetic fields (7 T/s) for plasma breakdown and configuration control. However, this operating mode significantly affects the stability of superconducting magnets. On one hand, the excitation process induces shielding current effects in the superconducting tapes, negatively impacting the uniformity and stability of the magnetic field. On the other hand, during rapid charging and discharging of the superconducting magnets, the instantaneous rate of current change is extremely high, leading to significant thermal accumulation effects. If there are pre-existing defects in the superconducting coils (such as impurities, cracks, or microscopic voids), these defects may become local hot spots. At these defective sites, the local temperature rises significantly, potentially causing the superconducting material in these areas to quench first, forming localized resistive regions.

Currently, superconducting magnet quench simulations are primarily conducted under steady-state current and background field conditions. However, due to the variation of the superconducting material's electrical and physical properties with magnetic field magnitude and angle, these simulations cannot fully represent quench propagation under alternating operation. Therefore, it is crucial to establish an electromagnetic field simulation model and a quench simulation model to analyze quench performance under alternating current operation. This study focuses on the superconducting magnet system in the next-generation compact fusion energy experimental device and develops a universally applicable method for quench simulation analysis under pulsed current operation. By integrating COMSOL electromagnetic simulations with CryoSoft quench simulations, the quench propagation characteristics of the CS coil LTS magnet in the next-generation compact fusion energy experimental device are thoroughly analyzed. The main tasks of this study include:

1. structing a three-dimensional model of the superconducting magnet system for the next-generation compact fusion energy experimental device, providing an accurate geometric foundation for subsequent simulation analyses.
2. Analyzing the three-dimensional distribution of complex alternating magnetic fields generated by each coil under pulsed current (plasma discharge) conditions in COMSOL. This provides a realistic background magnetic field for subsequent quench simulations, which is crucial for understanding the electromagnetic behavior of the magnet during actual operation.
3. ng the THEA program to perform a detailed analysis of the quench performance of the CS coil LTS magnet under the background field provided by the COMSOL simulation. This includes evaluating key parameters such as minimum quench energy and quench propagation velocity, providing theoretical guidance for the safe operation of the magnet and the design of quench protection systems.

Keywords: Pulsed (alternating) current, Quench simulation, Quench propagation, THEA program