Quench and Quench Protection for the SSC Collider Correctors

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Abstract

The quench voltage, especially the turn-to-turn voltage, and the maximal temperature rise due to the quench in 50-mm-aperture Superconducting Super Collider collider correctors are calculated for various currents. The calculation shows a lower copper-to-superconductor ratio gives a lower quench voltage and a lower temperature rise as the result of much higher heat capacity of the superconducting material and lower copper resistivity at lower temperature. It also shows that when the copper to superconductor ratio is 2.2 to 1, each individually powered magnet is self-protected, and for the series of 24 correctors that are powered together in the collider, a parallel 2Ω resistor on each magnet will provide needed protection. The energy loss on these resistors during powering up is less than 5% of the energy stored in the magnet at the operating current.

I. INTRODUCTION

When a quench occurs in a superconducting coil, the normal zone starts to grow so that the resistance of the magnet increases until all the stored electro-magnetic energy has dissipated through the ohmic heating[1]. This process causes temperature rise and high voltage in the coil. Can the quenches in the current Superconducting Super Collider (SSC) collider corrector design damage the superconducting windings?

In answering this question, we first study how the normal zone grows in the coil windings under the adiabatic assumption to find the way for calculating the time- and geometry-dependent coil resistance, $R_{mag}(t)$. Then we use a computer to simulate the electric circuit that includes the quenching magnet with the resistance, $R_{mag}(t)$. Finally, some suggestions on the quench protections will be made for the cases where excessive heat and/or voltage are expected by the simulation results.

II. NORMAL ZONE GROWTH AND ITS RESISTANCE

A typical cross section of the SSC collider corrector winding is rectangular, as shown in Figure 1. The area of each unit cell is A. The longitudinal (along the z-direction) normal zone growth velocity, v_l, is determined by the thermal properties of the metal part of the coil; it also depends on the current and conductor packing density [1][2][3]. The transverse velocity, v_t, is much smaller than the longitudinal one because of the much lower heat conductivity of the insulation. The ratio between the two is [1]

$$\alpha = \frac{v_t}{v_l} = \frac{(\gamma C)_{avm}}{(\gamma C)_{av}} \left\{ \frac{k_t}{k_l} \right\}^{1/2},$$

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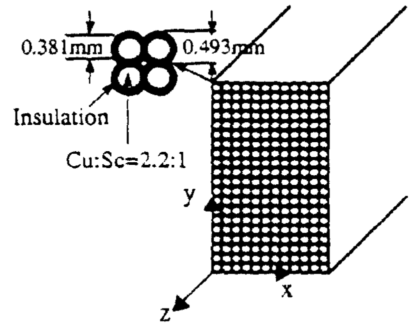

Figure 1. Typical section of coil winding in SSC collider correctors.

where $(\gamma C)_{av}$ and $(\gamma C)_{avm}$ are the volumetric heat capacity averaged over the whole coil cross section and the metallic constituents only, respectively; k_t is the transverse thermal conductivity determined by the insulation; and k_l is the longitudinal one mainly contributed from the copper and NbTi constituents. α is around 0.02∼0.03 for these corrector coils.

Therefore, at any time t after a quench starts at time $t = 0$, the normal zone is a rotating ellipse centered at the quench starting point. The rotating axis is longitudinal before it hits any coil boundary, or its two ends meet in one of the three directions [4]. The long axis of the elliptic is $v_l t$ and the two short ones are $\alpha v_l t$. When a coil boundary is encountered or two normal zone ends meet, the normal zone stops its growth on that direction, but continues on the other directions until the stored energy is exhausted or the whole coil turns normal, whichever comes first. The resistance $R(t)$ of this normal zone at any given time $t>0$ is evaluated by dividing the whole region into subregions according to their quenching time t' and a small time interval Δt. When the coil boundary is not involved, each subregion is a shell in the rotating elliptic, with long axis $v_l t'$ and shell thickness $v_l \Delta t$ on that direction. The MIITS value,

$$MIITS = \frac{1}{A} \int_{t'}^{t} I^2(\tau) d\tau,$$

is computed for each subregion. A comparison of this MIITS value to the temperature-MIITS tables for the copper and NbTi with the given RRR (residual resitivity ratio) value [5] is made to get the temperature rise in this subregion. The semi-empirical expression of the copper resistivity for the temperature range 0∼1000K [5],

$$\rho(T, RRR) = \frac{1.545}{RRR} + \left(\frac{2.32547 \times 10^9}{T^5} + \frac{9.57137 \times 10^5}{T^3} + \frac{1.62735 \times 10^2}{T} \right)^{-1},$$

is invoked to find the resistance. A summation of the subregion resistance over the normal zone is carried out to provide the magnet resistance, $R_{mag}(t)$.

Note that the adiabatic assumption has been used throughout the preceding calculation. There is no heat conducted out of the coil. Inside the coil, heat is also absorbed to produce the normal zone growth, but this latent heat is not deducted when the temperature rise of the conductors is evaluated. So an overestimate of temperature rise and resistance of the normal zone is expected from this procedure.

III. QUENCH CIRCUIT SIMULATION

The method to calculate the resistance of the corrector magnet coil during a quench was worked out in the previous section. One other important electric parameter is the inductance of the magnet. We use PE2D[1] to do two-dimensional field analysis and stored energy calculation for different currents. The circuit in Figure 2 is for a magnet powered individually. When a quench is detected, the switch is closed and the power supply is shut down. Usually a quench detection has a few millisecond delay to the quench itself, compared to the 100 ms to 200 ms for the whole quench time scale. This delay can be treated as zero without any significant impact on the results. The switch also can be replaced by a diode that introduces ~0.6 V voltage across the diode, but that voltage can be ignored compared to the hundreds to thousands of volts inside the magnets across the normal resistance zone.

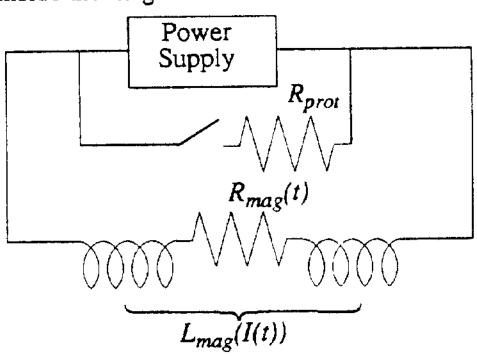

Figure 2. Quench circuit for individually powered corrector.

Assuming the quench starts in a corner of the coil winding at time $t = 0$ and quench current I_0, we have the initial conditions,

$$\begin{cases} \Delta t = 0.001\,\text{sec} \\ z[0] = 0 \\ I[0] = I_0 \\ R_{mag}[0] = 0 \\ \Delta I[0] = -I[0]R_{prot}\Delta t/L_{mag}(I_0) \\ MIITS_i[0] \equiv \dfrac{1}{A^2}\displaystyle\int_0^0 I^2[t']dt' = 0 \quad \text{for all integer } i \geq 0, \end{cases}$$

where $z[t]$ is the half-rotating axis of the normal zone ellipse (Figure 1).

At time $t = n\Delta t$, the iteration relations become

$$\begin{cases} z[n\Delta t] = z[(n-1)\Delta t] + \dfrac{I[(n-1)\Delta t]}{I_0}v_0\Delta t \\ I[n\Delta t] = I[(n-1)\Delta t] + \Delta I[(n-1)\Delta t] \\ \Delta I[n\Delta t] = I[(n-1)\Delta t)] + \Delta I[(n-1)\Delta t)] \end{cases}$$

and

$$R_{mag}[n\Delta t] = \frac{1}{4}\sum_{i=0}^{n-1} f(i)\frac{\pi a^2 \rho_{cu}(T([i, n\Delta t], RRR))}{\lambda_m A^2}$$
$$\times \{z[(i+1)\Delta t] + z[i\Delta t]\}^2\{z[(i+1)\Delta t]-z[i\Delta t]\}$$

where λ_m is the proportion of the metal constituents in the coil unit cell, and element i ($<n$) is the subregion of the ellipse mentioned in the previous section, which turns to normal at time $t' = i\Delta t$. Its temperature $T[i, n\Delta t]$ is evaluated via the MIITS iteration formulas.

$$MIITS_i[n\Delta t] = MIITS[(n-1)\Delta t)] + \frac{I^2[(n-1)\Delta t)]}{A^2},$$

and the MIITS tables in Reference [5].

IV. RESULTS

An SSC collider dipole corrector with the winding configuration shown in Figure 1 has the following additional paramaters:

Maximal operating field	2.21 T
Coil width	10.84 mm
Coil height	24.15 mm
Coil length	1.36 m
Number of coils	2
Inductance	2.4 H
Maximal operating current (60% wire short sample)	86 A.

The calculated maximal turn-to-turn voltage, maximal resistive voltage across the normal zone, and temperature rise of the conductor in which the quench starts under various currents are plotted in Figure 3. It shows that the turn-to-turn voltage will not exceed 210 V, the total resistive voltage across the resistance of the normal zone is less than 2000 V, and the temperature rise in the hottest spot is less than 300 K when the magnet is operated below the maximal operating current 86 A. Therefore the magnet is self-protected during the collider operation. Figure 3 also shows that during the magnet quench testing, when the current exceeds 105 A, some protection measure should be taken to prevent any damage in the insulation due to overheating.

All the other collider arc correction magnets are smaller than the dipole corrector, so they are all self-protected when they are individually powered. But when 24 quadrupole or sextupole correctors are connected in series, the inductance will be higher than 45 H, and the single quenching magnet cannot absorb the tremendous energy stored in all 24 magnets. So a current bypass system is necessary to protect this magnet. A 2-Ω resistor can be connected parallel to each member in the series for the protection. To minimize the influence of single

[1] PE2D is a trademark of the Vector Field, Inc.

magnet quench on the corrector system operation, two opposite parallel diodes are preferred rather than one resistor for the bipolar current operation.

Quench simulations are also done for different copper-superconductor ratios of the superconducting wire around 2.2:1. It shows that higher superconductor contents lower the quench voltage across the normal resistance zone and the temperature rise caused by the quench. We believe that in our range of study, the much higher heat capacity of the NbTi and lower copper resistivity at a lower temperature are the source of this effect.

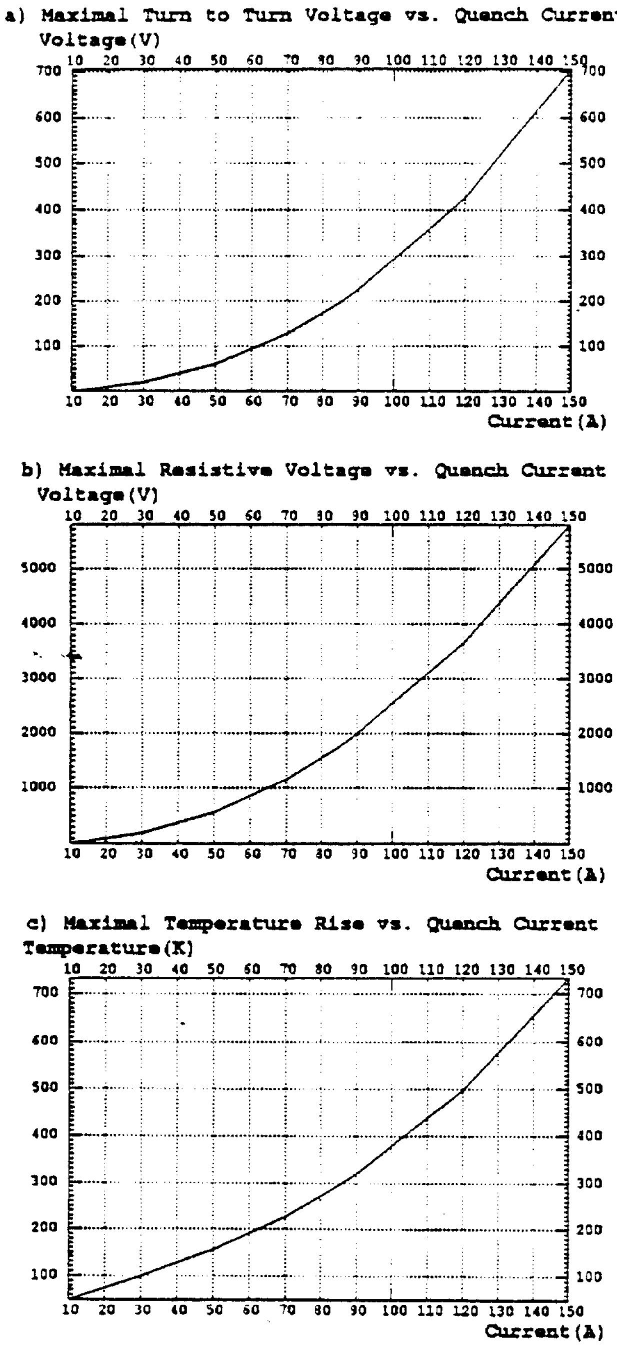

Figure 3. SSC collider dipole corrector quench data.

The simulation code is also checked with the testing data for some prototype correction magnets. A comparison is shown in Figure 4 for the current decay over time. The difference is believed due to ignoring the cooling effect mentioned in Section II.

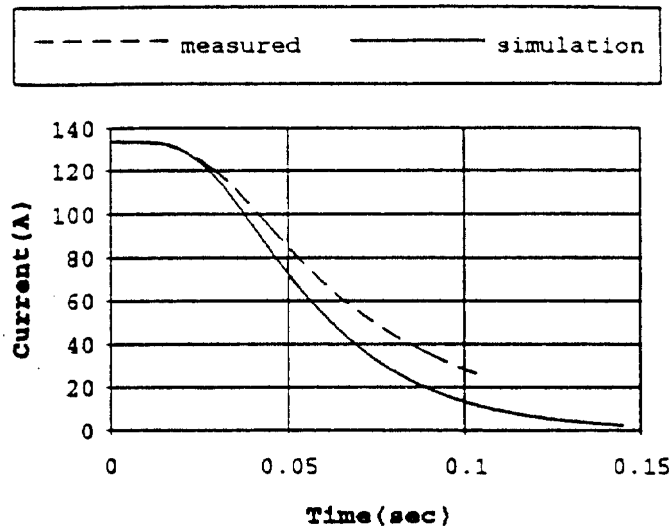

Figure 4. A comparison between the simulation and measured current decay for an SSC corrector dipole prototype.

V. ACKNOWLEGEMENT

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