Quench Protection of a High Gradient Quadrupole for the LHC Interaction Regions

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Abstract—The energy stored in a superconducting (SC) accelerator magnet is usually dissipated after a quench in the normal zones of the coil, heating the coils and producing a voltage drop between the turns inside the magnet and between coil and ground. This paper presents the results of the analysis of the quench protection problem for a high gradient quadrupole for the LHC interaction regions.

I. INTRODUCTION

High gradient SC quadrupoles (HGQ) for the LHC Interaction Region (IR) are being developed now at CERN [1] and FNAL [2]. The main parameters of these magnets, specified by the LHC Conceptual Design [3] are: a bore diameter of 70 mm, a nominal field gradient of 235 T/m and a magnetic length of 5.5 m. These magnets will operate in high radiation environments [4,5] which may cause magnet quenches, and they have to be reliably protected during a quench.

The normal zone in the quadrupole coil can appear in the inner or outer layer. If this zone is small so that the resistive voltage drop is less than the quench detector threshold, it will increase in size because of quench propagation and cable heating for some time before the quench detector detects it. The power supply will be then disconnected, the magnet is shorted and the quench heaters are fired. The current in the magnet will decay to zero with the growth of coil normal resistance and the energy stored in the magnet will dissipate in the normal zones of the coil producing heating, thermal expansion and voltage drop between the turns inside the magnet and between coil and collars, which are connected to ground.

The main dangers for the SC magnet during a quench are coil overheating and mechanical overstress as well as high voltage between the turns inside the magnet and between the magnet coil and ground. These factors can change the magnet operation parameters or destroy it. The magnet design and cable parameters as well as the parameters of the quench protection system should be chosen and optimized in such a way to provide a reliable magnet protection during a quench.

This paper presents the results of the quench protection problem analysis for the HGQ being developed at Fermilab for the LHC interaction regions.

II. HGQ DESIGN

The Fermilab/LBNL HGQ design features are described in [2]. It consists of four, two layer coils connected in series. The coils are mechanically supported by means of the collar laminations, cold iron yoke and helium vessel shield. Inner diameter of the collared coil is 70 mm. Each coil consists of 30 turns, 14 in the inner and 16 in the outer layer, and two spacers in each octant, one in the inner and one in the outer layer. The magnet inductance is 3.48 mH/m and the stored energy at the nominal current of 13 kA is 294 kJ/m.

Two keystoned Rutherford-type superconducting cables based on the SSC type strands are used in the quadrupole design. The main HGQ conductor and cable parameters are presented in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Inner cable</th>
<th>Outer cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable width</td>
<td>mm</td>
<td>15.4</td>
<td>15.4</td>
</tr>
<tr>
<td>Minor edge</td>
<td>mm</td>
<td>1.326</td>
<td>1.054</td>
</tr>
<tr>
<td>Major edge</td>
<td>mm</td>
<td>1.587</td>
<td>1.238</td>
</tr>
<tr>
<td>Number of strands</td>
<td></td>
<td>38</td>
<td>46</td>
</tr>
<tr>
<td>Strand diameter</td>
<td>mm</td>
<td>0.808</td>
<td>0.648</td>
</tr>
<tr>
<td>Cu/SC ratio</td>
<td></td>
<td>1.3:1</td>
<td>1.8:1</td>
</tr>
<tr>
<td>Strand RRR</td>
<td></td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

The maximum design gradient for the SSC superconductor is 250 T/m at the current 13.8 kA. It is expected to increase the critical current density in the superconducting wires for the HGQ from 2.75 to 3.4 kA/mm² at 5 T and 4.2 K and to decrease simultaneously Cu:Sc ratio in the inner layer cable from 1.3 to 1.1 and in the outer layer cable from 1.8 to 1.6. This will allow one to increase the quadrupole maximum field gradient up to 270 T/m and to provide higher coil temperature margin and stability to the short heat pulses.

To protect the magnet during a quench, quench heaters will be used. A two layer design allows one to put the heaters on the coil outer layers or between the inner and outer layers. Since interlayer heaters can provide better heater efficiency, they have been chosen as a baseline. Each interlayer heater can quench one side of 10 inner layer turns and one side of 15 outer layer turns in two neighboring coils. The length of each heater is equal to double the magnet length, or 11 m. The number of heaters in the magnet is four (two of them are operating and two are spare).
III. QUENCH ANALYSIS

A. Coil Heating

Coil heating after a quench in adiabatic conditions is determined by the equation

\[ \int_0^t \frac{(t)^2}{T(t)} dt = N^2 S^2 \gamma \int \frac{C(T)}{\rho(T)}dT, \quad (1) \]

where \( I(t) \) - current decay after a quench; \( T(t) \) - coil temperature; \( T_c \) - conductor critical temperature; \( N \) - number of strands in the cable; \( S \) - strand cross-section; \( C(T) \) - strand specific heat; \( \rho(T) \) - strand resistivity; \( \gamma \) - strand mass density.

The maximum temperature \( T_{\text{max}} \) is achieved when \( t \rightarrow \infty \). It is function of the quench integral (left side of (1)) and cable parameters. The relationship between \( T_{\text{max}} \) and quench integral for the quadrupole inner and outer cables is presented in Figure 1. To keep the cable temperature during a quench below 400 K, as in the LHC arc dipoles \[3\], the quench integral has to be less than \( 25 \times 10^6 A^2s \) for the inner layer cable and \( 17 \times 10^6 A^2s \) for the outer layer one.

![Figure 1. Relationship between the cable maximum temperature and quench integral:](image)

The maximum value of the quench integral depends on the magnet current \( I_0 \), the quench detection and circuit operation time, \( \tau_D \), as well as the current decay after heater induced quench, \( I(t) \),

\[ \int_0^\infty I(t)^2 dt = I_0^2 - \tau_D + \int_0^{\tau_D} I(t)^2 dt, \quad (2) \]

The dependence of the quench integral corresponding to the current decay after heater induced quench vs. magnet operating current is shown in Figure 2. Quench integral value is the same for all turns in the magnet quenched by the heaters. As follows from the data, presented in Figures 1 and 2, for the same current and the same quench integral, the outer layer cable is heated to a higher temperature than the inner layer one. The heater induced quench integral at the nominal current 13 kA equals to \( 11 \times 10^6 A^2s \) and the outer layer turns, quenched by heaters, is heated to the maximum temperature of 155 K and the inner layer one to 85 K.

![Figure 2. Dependence of the quench integral vs. magnet current.](image)

B. Delay Time Limit

Based on the maximum quench integral budget and the value of heater induced component of the quench integral, one can determine the upper limit for the quench detection and circuit operation time (delay time). Results of the calculations of the maximum delay time for the inner and outer cables as a function of the magnet current are presented in Figure 3.

![Figure 3. Dependence of the circuit operation time (delay time) vs. magnet current:](image)

As can be seen, the upper limit for the quench detection and circuit operation time at nominal current of 13 kA is 85
ms in the case of quench in the inner layer cable and 40 ms for the outer layer cable. These limits look reasonable and can be practically realized.

C. Mechanical Stress

The quenched turns in the magnet will produce a coil thermal expansion within the cold collars. As a result, the stress in the coil will increase. Stress growth is determined by the coil elasticity modulus, thermal expansion coefficient, fraction of quenched turns and their temperature. The inner and outer layer mechanical stress, calculated for the quench at nominal current 13 kA, vs. temperature for chosen heater surface is shown in Figure 4. It is assumed that thermal expansion and the elasticity modulus of the coil follow a parabolic temperature dependence.

A mechanical stress reaches the maximum value of ~28 MPa in the inner layer and ~35 MPa in the outer layer at the coil temperature of 250-300 K. Since the maximum temperature for most of the turns quenched by heaters is relatively small, the additional stress in the coil during a quench will be less than 15 MPa in the outer layer and less than 5 MPa in the inner one.

D. Quench Voltages

Electrical voltages are developed in the magnet during a quench. In the case when all four coils are quenched by heaters (normal operation with two heaters), the total voltage across all coils equals to zero. Coil-to-coil voltage inside the magnet in that case also equals to zero. Maximum coil-to-ground voltage, $U_{cg}$, is applied to the point between the inner and outer layers of each coil near magnet poles. Turn-to-turn voltage, $U_{tr}$, which developed in the coil during a quench is a sum of the resistive, $U_R$, and inductive, $U_L$, components.

Some examples of the time dependence of the turn-to-turn voltage and of the coil-to-ground voltage after a heater induced quench, computed for the nominal current of 13 kA, are presented in Figures 5 and 6.

As can be seen from the above plots, maximum turn-to-turn voltage in the inner layer is ~10 V and in the outer one is ~25 V. Maximum coil-to-ground voltage does not exceed 200 V.

When the quench is induced by only one heater, the voltage distribution depends on the heater position in the magnet. Significant coil-to-ground and coil-to-coil voltages are developed in the magnet during quench. Maximum coil-to-ground voltage in this case exceeds 1 kV and maximum coil-to-coil voltage is 1.5-2 times higher than coil-to-ground voltage. Analysis shows that an operation of the quench protection system with only one heater is dangerous for the magnet insulation and so can not be allowed.
**E. Design Quench Protection Margin**

The critical current density in the superconducting strands will be increased from 2.75 to 3.4 kA/mm² at 5 T and 4.2 K and simultaneously Cu:Sc ratio will be decreased in the inner layer cable from 1.3 to 1.1 and in the outer layer one from 1.8 to 1.6. This will allow one to increase the maximum field gradient up to 270 T/m and the coil inner layer stability to the short heat pulses. The nominal field gradient could be increased up to 250 T/m and operating current up to 14 kA.

The results of the calculations of the major quench parameters for the HGQ with new improved superconducting strands operating at currents of 13 kA and 14 kA are summarized in Table II.

<table>
<thead>
<tr>
<th>Magnet current, kA</th>
<th>Coil layer</th>
<th>$T_{max}$ K</th>
<th>$\tau_{df}$ ms</th>
<th>$U_{in}$ V</th>
<th>$U_{eg}$ V</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>inner</td>
<td>85</td>
<td>76</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>outer</td>
<td>155</td>
<td>43</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>inner</td>
<td>90</td>
<td>63</td>
<td>15</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>outer</td>
<td>170</td>
<td>35</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

As it follows from the above table, the expected reduction of copper-to-superconductor ratio in the inner and outer cables as well as possible increase of magnet operating current do not change significantly the main magnet quench parameters.

The effect of the magnet length on the HGQ quench protection was also analyzed. It is easily to understand that magnet length affects the value of the voltages in the coil and does not affect the coil maximum temperature and mechanical stress after a quench. Data presented above show that quench protection can be safely provided for a HGQ with a length up to 11 m. Maximum turn-to-turn and coil-to-ground voltages in this case will not exceed 60 V and 500 V respectively. Maximum temperature of the coil inner and outer layer, and additional mechanical stress in the layers during quench are the same as for the 5.5 m long magnet.

**V. CONCLUSIONS**

Quench protection of a HGQ, being developed at Fermilab in collaboration with LBNL and BNL for the LHC interaction regions, can be reliably provided with two quench heaters placed between the coil inner and outer layer. Maximum values of the electrical voltages, layers temperature and stress during a quench will be within safe limits close to those for the arc LHC dipoles [1]. Operation with only one heater is not recommended because of significant voltage drop between the coils inside the magnet and between the coil and ground.

Developed magnet design has a sufficient quench protection margin with respect to the changes of some conductor and magnet parameters. The reduction of the Cu/Sc ratio in the inner and outer layer cables as well as possible increase of the magnet length and operating current will not change significantly the basic quench protection parameters of the magnet.

**REFERENCES**


