An Inverse Calculation Study on Post-Quench Behavior of a No-Insulation REBCO Insert

Chaeimin Im1, Soobin An1, Jeseok Bang1, Jaesik Kim1, Kabindra R. Bhattarai2, Kwang Lok Kim2, Kwangmin Kim2, and Seungyong Hahn1

1Department of Electrical and Computer Engineering, Seoul National University, Seoul 08805, South Korea.
2National High Magnetic Field Laboratory, Tallahassee, FL 32310 USA.

Abstract: This paper proposes an approach to account for a fast electromagnetic quench propagation among electromagnetically coupled ni-ruodurc (HTS) coils. Recently, multiple groups have reported that the conventional lumped-circuit model, which has well demonstrated charging and discharging behaviors of an HTS magnet, could not account for post-quench behaviors. Specifically, terminal voltages of individual pancake coils were estimated to be too high than the simulated ones. This paper proposes an approach that focuses on the post-quench simulation of an HTS HTS magnet. To explain this phenomenon as a lumped circuit, a new approach was introduced. The key idea is inversely calculating key parameters of the lumped circuit that best demonstrates the non-linear post-quench behaviors. After defining the necessary assumptions, we adopted inverse calculating methods to analyze the test results of high-field HTS magnets. Simulation results suggest that after a quench, the index resistance changes in a different way from the previous theory, while the change in characteristic resistance is similar to conventional theory.

Keywords: Inverse Calculation, Electromagnetic Quench, Lumped Circuit, REBCO, Superconducting Magnet

Introduction

- Challenges of Lumped Circuit
  - Uncertainty of circuit variable to fully explain the nonlinear behavior of Ni REBCO magnets.
  - Limited understanding on the equivalent circuit parameters.
  - Substantial discrepancy between simulation and results from quench test [1].
- Investigation of the Temporal Behaviors of Key Parameters of the Lumped Circuit.
  - Key parameters: Index resistance $R_i$, and characteristic resistance $R_c$.
- Goal: Finding behaviors of these parameters to account for the post-quench voltage.

Approach: Inverse Calculation

Table 1. Key parameters of 45.5 T insert magnet [1]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average width</td>
<td>[mm]</td>
<td>4.02</td>
</tr>
<tr>
<td>Thickness of coil</td>
<td>[mm]</td>
<td>0.01</td>
</tr>
<tr>
<td>Inner radius, outer radius</td>
<td>[mm]</td>
<td>7.17</td>
</tr>
<tr>
<td>Total height</td>
<td>[mm]</td>
<td>53.1</td>
</tr>
<tr>
<td>Number of single pancakes</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Average turns per single pancake</td>
<td></td>
<td>2256</td>
</tr>
<tr>
<td>Operating current before quench</td>
<td>mA</td>
<td>245.3</td>
</tr>
<tr>
<td>Characteristic resistance at 4.2 K</td>
<td>[mΩ]</td>
<td>81.7</td>
</tr>
<tr>
<td>Magnet resistance</td>
<td>[mΩ]</td>
<td>6.04</td>
</tr>
</tbody>
</table>

Fig 4. Results of inverse calculation. Profiles of (a) experimentally measured voltage (solid) and simulated voltage (dashed), (b) simulated mutual current.

$V_i = I_{op} R_i + \sum M_i \frac{d I_i}{dt} = I_{op} R_i + I_{op} R_c$

$V_i$: Voltage of P DP
$R_i$: Azimuthal resistance of P DP
$R_c$: Index resistance of P DP
$R_{op}$: Radial current of P DP
$M_i$: Characteristic resistance of P DP
$M$: Mutual Inductance between P and P DP

$V_i$: Voltage of P DP
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$W$: Cost f.: # of DP $V_i$, $V_i$ of DP $V_i$ of DP $V_{sum}$ of each DP Current $I_{op}$, Current $I_{op}$ $\theta_i$ angle

$W = \sum_{i=1}^{N} \left( \alpha_i \theta_i \right)^2 R_{op}(\theta_i) + \left( \beta_i \theta_i \right)^2 R_i(\theta_i) + \gamma \left( \theta_i \right)^2 R_{int}(\theta_i) + \gamma \left( \theta_i \right)^2 R_c(\theta_i)$

$V_{sat} = V_{sum} = \sum_{i=1}^{N} \left( \alpha_i \theta_i \right)^2 R_{op}(\theta_i)$

$V_i$: Voltage of DP $i$
$R_i$: Characteristic resistance of DP $i$
$\alpha_i$: Slope of $i$-th characteristic resistance
$\beta_i$: Slope of $i$-th characteristic resistance
$\theta_i$: Current angle at $i$-th DP
$R_{op}(\theta_i)$: Operating current at $i$-th DP
$R_c(\theta_i)$: Characteristic resistance at $i$-th DP
$V_{sat}$: Input voltage
$V_{sum}$: Total voltage

$E = V_f \left( \frac{R_{op}}{2} + \frac{R_c}{2} \right) D_f$

$V_f$: Total volume of coil
$D_f$: Cost / W

$Y_j$: Sum of total voltage seems to be saturated (Fig. 3)

$V_{sum} = \sum_{i=1}^{N} \left( \alpha_i \theta_i \right)^2 R_{op}(\theta_i)$

$\theta_i$: Current angle at $i$-th DP
$R_{op}(\theta_i)$: Operating current at $i$-th DP
$R_c(\theta_i)$: Characteristic resistance at $i$-th DP
$V_{sum}$: Total voltage

$W$: Cost f.: # of DP $V_i$, $V_i$ of DP $V_i$ of DP $V_{sum}$ of each DP Current $I_{op}$, Current $I_{op}$ $\theta_i$ angle

$W = \sum_{i=1}^{N} \left( \alpha_i \theta_i \right)^2 R_{op}(\theta_i) + \left( \beta_i \theta_i \right)^2 R_i(\theta_i) + \gamma \left( \theta_i \right)^2 R_{int}(\theta_i) + \gamma \left( \theta_i \right)^2 R_c(\theta_i)$

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$\beta_i$: Slope of $i$-th characteristic resistance
$\theta_i$: Current angle at $i$-th DP
$R_{op}(\theta_i)$: Operating current at $i$-th DP
$R_c(\theta_i)$: Characteristic resistance at $i$-th DP
$V_{sat}$: Input voltage
$V_{sum}$: Total voltage

Limitation of Time Range: Due to Voltage Characteristics of DP 1

- Peculiarities of Voltage of DP 1 & Sum of Total Voltage
  - No sudden change in voltage (both rise and fall, Fig. 1)
  - Sum of total voltage seems to be saturated (Fig. 3)
- Voltage of DP 1 is similar with $V_{sum}$ - Sum of the remaining DPs' voltages from 25-35 [mV] ($V_{sat} = 0.81 [V]$)
- After ~35 [ms], sum of total voltage shows totally different trend.
- In addition, the sudden change of the total voltage and $V_1$ out of trend near 45 [ms] seems to be due to the measurement error in DP 1.
- Due to these measurement uncertainties, only the 11-36 [ms] interval was analyzed.

Inverse Calculating Methods & Results of Voltage and Azimuthal Current

- Evolution Strategy
  - The resistances from the previous step become the “parent” generation.
  - The resistances of child generation have three options; they may be increased, decreased or unchanged from the parent generation values.
  - Then the values with the lowest cost are selected for the next parent step.
  - With $\alpha_i = 0.06$ and $\beta_i = 0.013$, temporal average cost was 0.027% less than the previous report, where 7 times increment of the characteristic resistance was observed.

- Results of Index Resistance and Characteristic Resistance
  - The index resistance of each DP increased rapidly as the voltage of the DP starts to rise.
  - Above $R_{op} \theta_i$, the index resistance increases linearly.
  - With adiabatic assumption, near final temperature, the stored energy of each DP is almost exhausted and increased heat capacity would slow down the increase of index resistance.
  - The characteristic resistance of all DP increased 4-13 times throughout the quench, which is in agreement with the conventional results [4].

- Determination of Threshold Resistance: Based on Final Temperature
  - The total energy $E$ stored in insert coil at the moment of quench: $1516.1$ J.
  - The final average temperature $T_f$ of the insert coil obtained form the energy conversion equation was $75 K$.
  - Therefore, with resistivity of 72 K, the $R_{op} \theta_i$ was set as $5.7 \Omega$.

Conclusion

- The index resistance increased significantly as the voltage increase in the beginning of the quench propagation, and increased linearly after the resistance reached at a certain threshold that was determined by the highest temperature calculated in an adiabatic energy conservation.
- The 4.13 time increment in characteristic resistance after the quench propagation was similar to the previous report, where 7 times increment of the characteristic resistance was observed.