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

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Abstract - This paper proposes an approach to account for a fast electromagnetic quench propagation among electromagnetically coupled no-insulation(NI) high temperature superconductor (HTS) coils. Recently, multiple groups have reported that the conventional lumped-circuit model, which has well demonstrated charging and discharging behaviors of an NI 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 NI 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 NI 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.

◆ 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_θ) and characteristic resistance resistance(R_r) [2].

Goal: Finding behaviors of these parameters to account for the post-quench voltage.

◆ Approach: Inverse Calculation

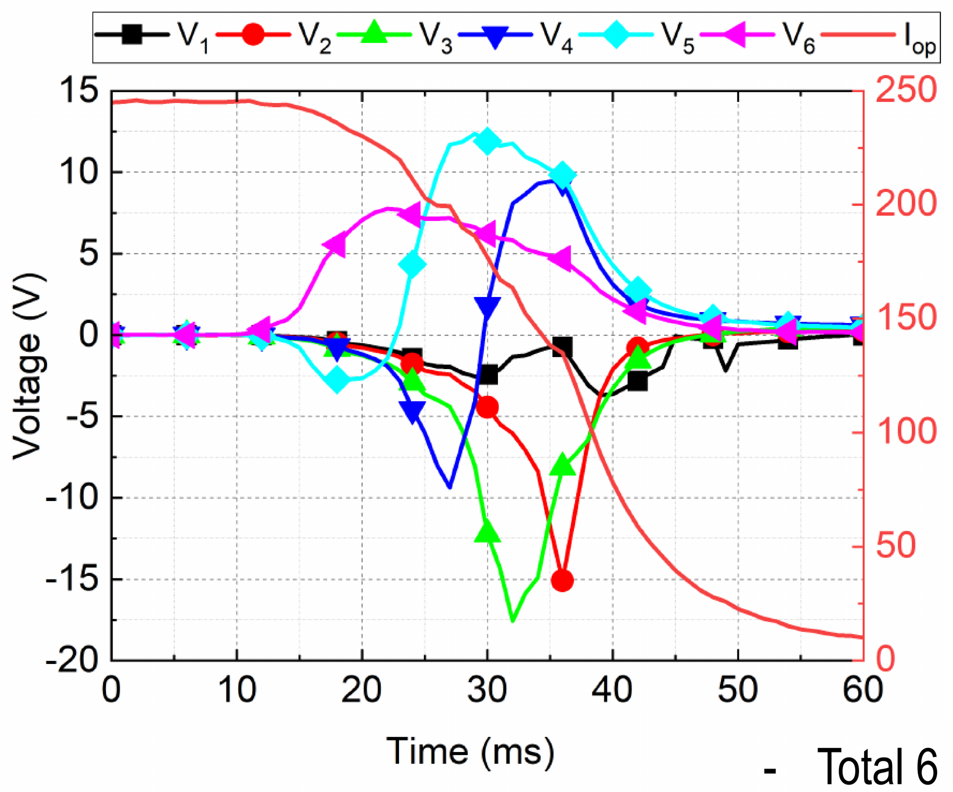

Fig 1. Voltage of all DPs and the operating current from 45.5 T quench test [1].

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

Parameters	Units	Value
Average width; average thickness	[mm]	4.02; 0.043
Thickness of copper	[mm]	0.01
Inner radius; outer radius	[mm]	7; 17
Total height	[mm]	53.1
Number of single pancakes		12
Average turns per single pancake		226.4
Operating current before quench	[A]	245.3
Characteristic resistance at 4.2 K	[mΩ]	47.1
Magnet inductance	[mH]	50.4

- Total 6 DPs, quench propagation time: 50 [ms]
- A quench has propagated from DP 6 (bottom) to DP 1 (top)
- With key parameters of lumped circuit, experimental voltages were inversely calculated.

- **Key Equations of Lumped Circuit**

$$V_i = I_{\theta i}R_{\theta i} + \sum_{j=1}^{n} M_{ij}\frac{dI_{\theta i}}{dt} = I_{ri}R_{ri}$$

$$I_{op} = I_{\theta i} + I_{ri}$$

V_i: Voltage of i[th] DP
$I_{\theta i}$: Azimuthal current of i[th] DP
$R_{\theta i}$: Index resistance of i[th] DP
I_{ri}: Radial current of i[th] DP
R_{ri}: Characteristic resistance of i[th] DP
M_{ij}: Mutual inductance between i[th] and j[th] DP
I_{op}: Operating current

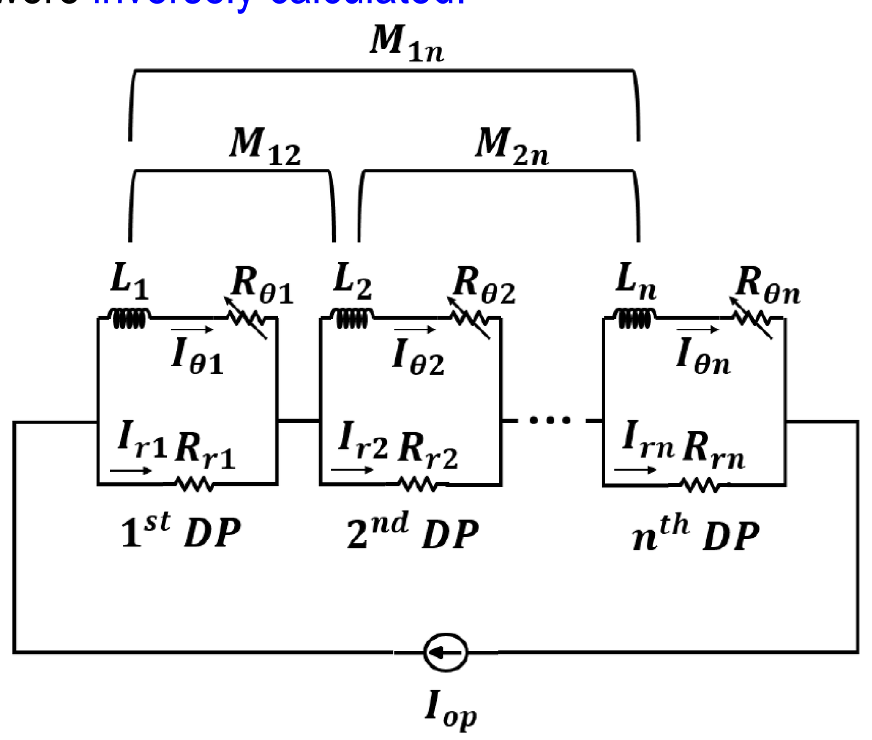

Fig 2. A lumped circuit model of n-DPs [3].

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

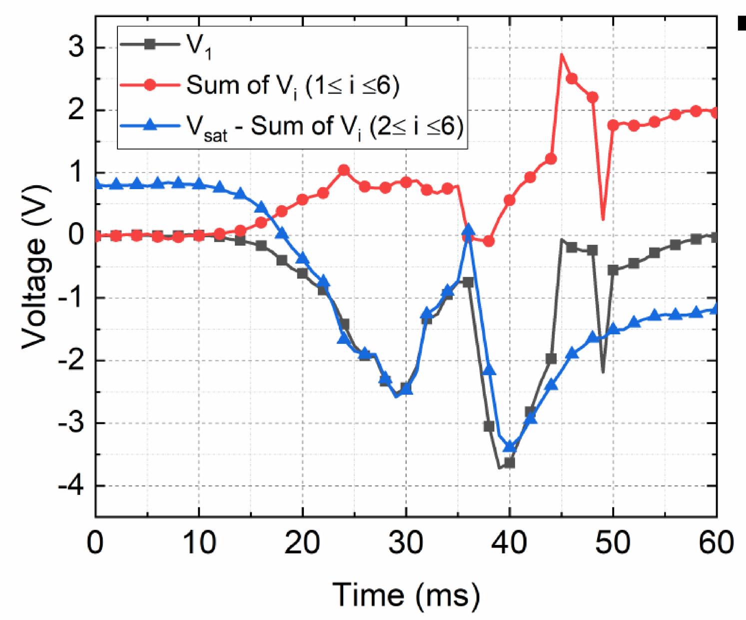

Fig 3. Profiles of V_1, Sum of $V_i (1 \le i \le 6)$, and V_{sat} −Sum of $V_i (2 \le i \le 6)$.

- **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_{sat} - sum of the remaining DPs' voltages from 25-35 [ms] (V_{sat} = 0.8 [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 time 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 α_1=0.6 and α_2 = 0.013, temporal average cost was 0.057; most of errors originated from fluctuation

$$W = \frac{1}{n}\sum_{i=1}^{m}\left|V_{cal}^{i} - V_{exp}^{i}\right|$$

$$R_{\theta i}(t_n) = \begin{cases} (1+\alpha_1)^{\beta_1}R_{\theta i}(t_{n-1}) \\ (if\ R_{\theta i}(t_{n-1}) < R_\theta^{th}) \\ R_{\theta i}(t_{n-1}) + \gamma \\ (if\ R_{\theta i}(t_{n-1}) \ge R_\theta^{th}) \end{cases}$$

$$R_{ri}(t_n) = (1+\alpha_2)^{\beta_2}R_{ri}(t_{n-1})$$

W: Cost / n: # of DP / V_{cal}^{i}: Calculated voltage of i[th] DP / V_{exp}^{i}: Measured voltage of i[th] DP / α_1, α_2: Rate of change of each resistance / β_1, β_2: -1, 0, or 1 /t_n: n[th] time step / γ: constant proportional to the slope of the temperature-dependent resistivity / R_θ^{th}: Threshold value of index resistance

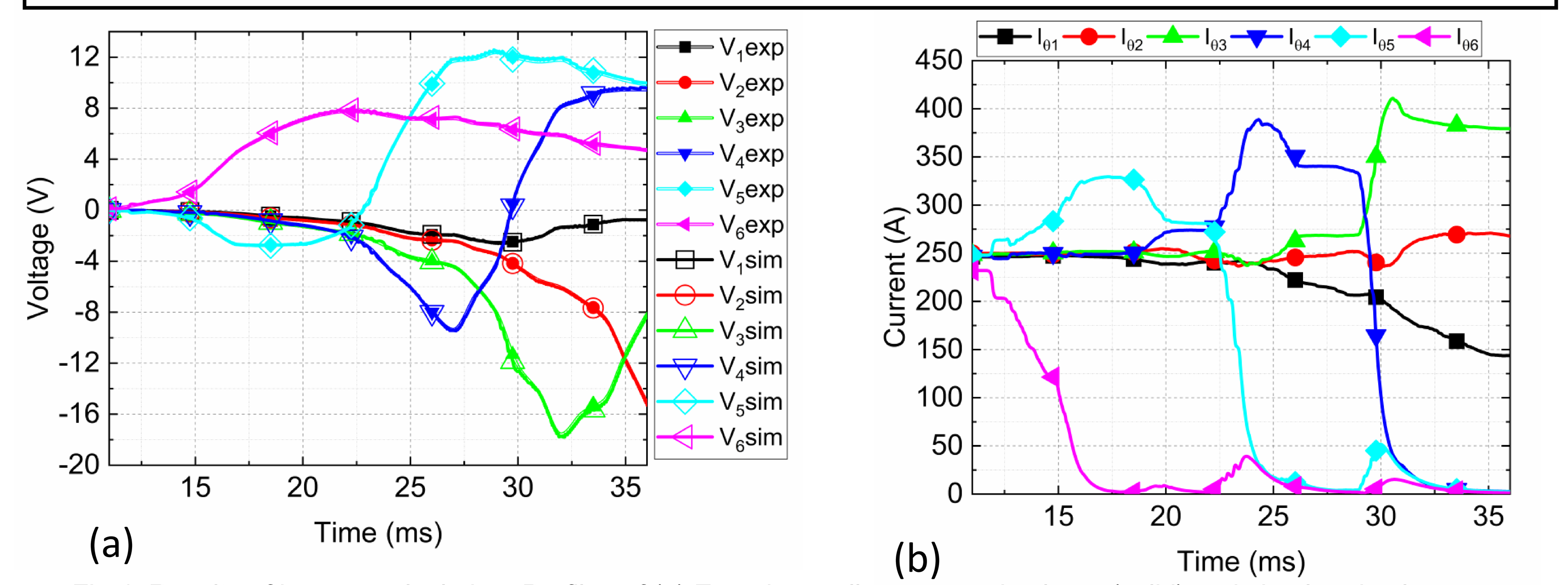

Fig 4. Results of inverse calculation. Profiles of (a) Experimentally measured voltage (solid) and simulated voltage (hollow); (b) simulated azimuthal current.

◆ Results of Index Resistance and Characteristic Resistance

- **Temporal Changes in Index Resistance and Characteristic Resistance**
  - The index resistance of each DP increased rapidly as the voltage of the DP starts to rise.
  - Above R_θ^{th}, 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 somewhat 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 [J]
  - The final average temperature T_f of the insert coil obtained form the energy conversion equation was 75 [K]
  - Therefore, with resistivity of 70 [K], the R_θ^{th} was set as 5.7 Ω

V: total volume of coil
$C(T)$: heat capacity

$$E = \int_{4.2\,K}^{T_f} VC(T)dT$$

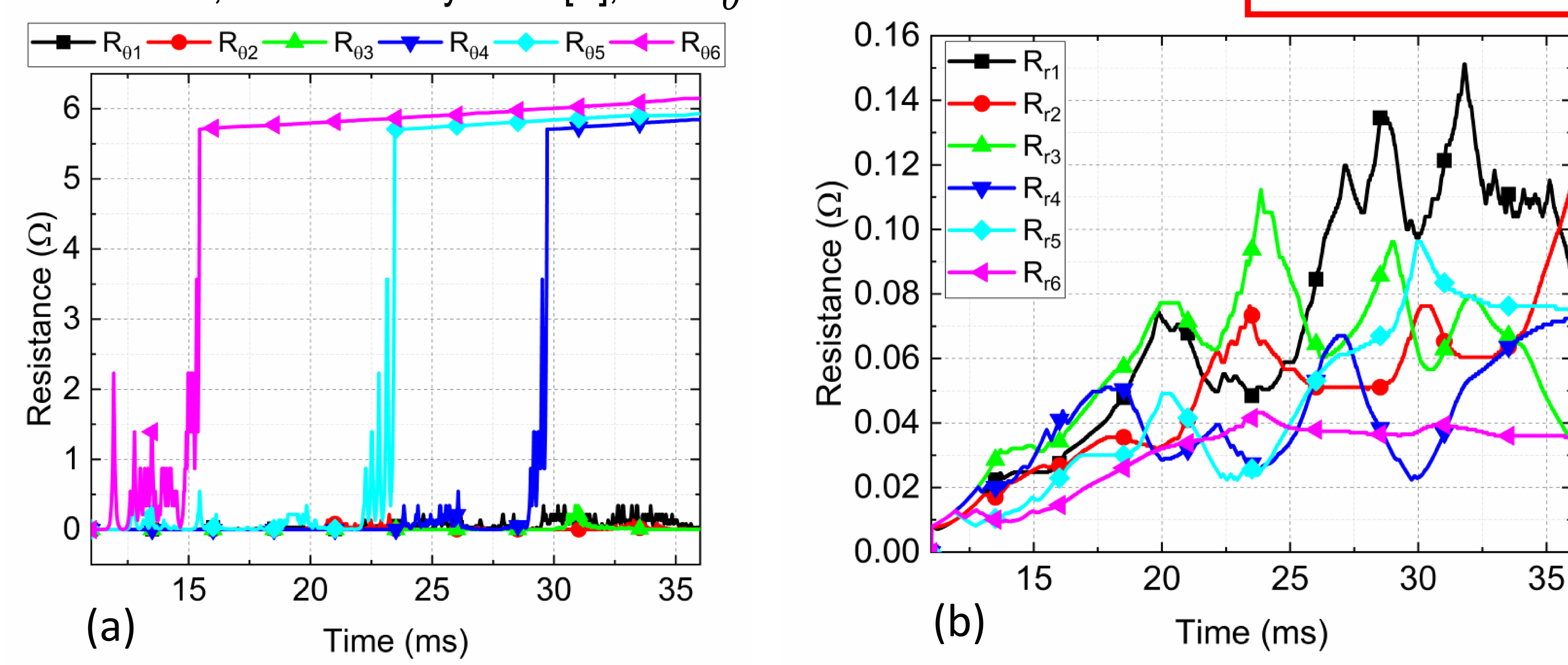

Fig 5. Results of inverse calculation. Profiles of (a) simulated index resistance; (b) simulated characteristic resistance.

◆ 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 from an adiabatic energy conservation.
- The 4-13 time increment in characteristic resistance over the quench propagation was similar to the previous report, where 7 times increment of the characteristic resistance was observed.

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