Post-quench Analyses of No-Insulation REBCO Pancake Using Electromagnetic-thermal Model

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Abstract

This study presents an electromagnetic-thermal model to simulate post-quench behaviors of a no-insulation (NI) $REBa_2Cu_3O_y$ (REBCO) pancake. The temperature-field-angle dependent critical current was always the connection bridge among the several physics modules, which was determined by a neural network fitting model in this study. The entire simulation model was developed by the combination between MATLAB and COMSOL, where adaptive simulation size was used on different phases to accelerate the simulation time. The simulation was conducted by a NI test coil and compared with experiment data. From the simulation result, we found the azimuthal current will gradually saturate and approach the magnet critical current and decrease at a similar rate when it is greater than the magnet critical current. Moreover, a cut-off voltage was determined from the simulation, and the corresponding sudden-discharging simulation was also studied.

Introduction

- The over-current simulation of no-insulation (NI) pancake is the fundamental work for magnet post-quench analyses. In the experiment test, the entire process is categorized into four phases: linear increase phase, saturation phase, cliff-type falling phase, and stabilizing phase [1].
- There are many poorly physical properties of second generation high temperature superconductor (2G HTS) with significant uncertainty that must be modeled [2].
- In the post-quench analysis, the temperature-field-angle dependent critical current is an important parameter to describe the superconductor property. Moreover, several physics modules should be considered, such as equivalent circuit model, magnetic module, thermal module.

Electromagnetic-thermal Model Flowchart

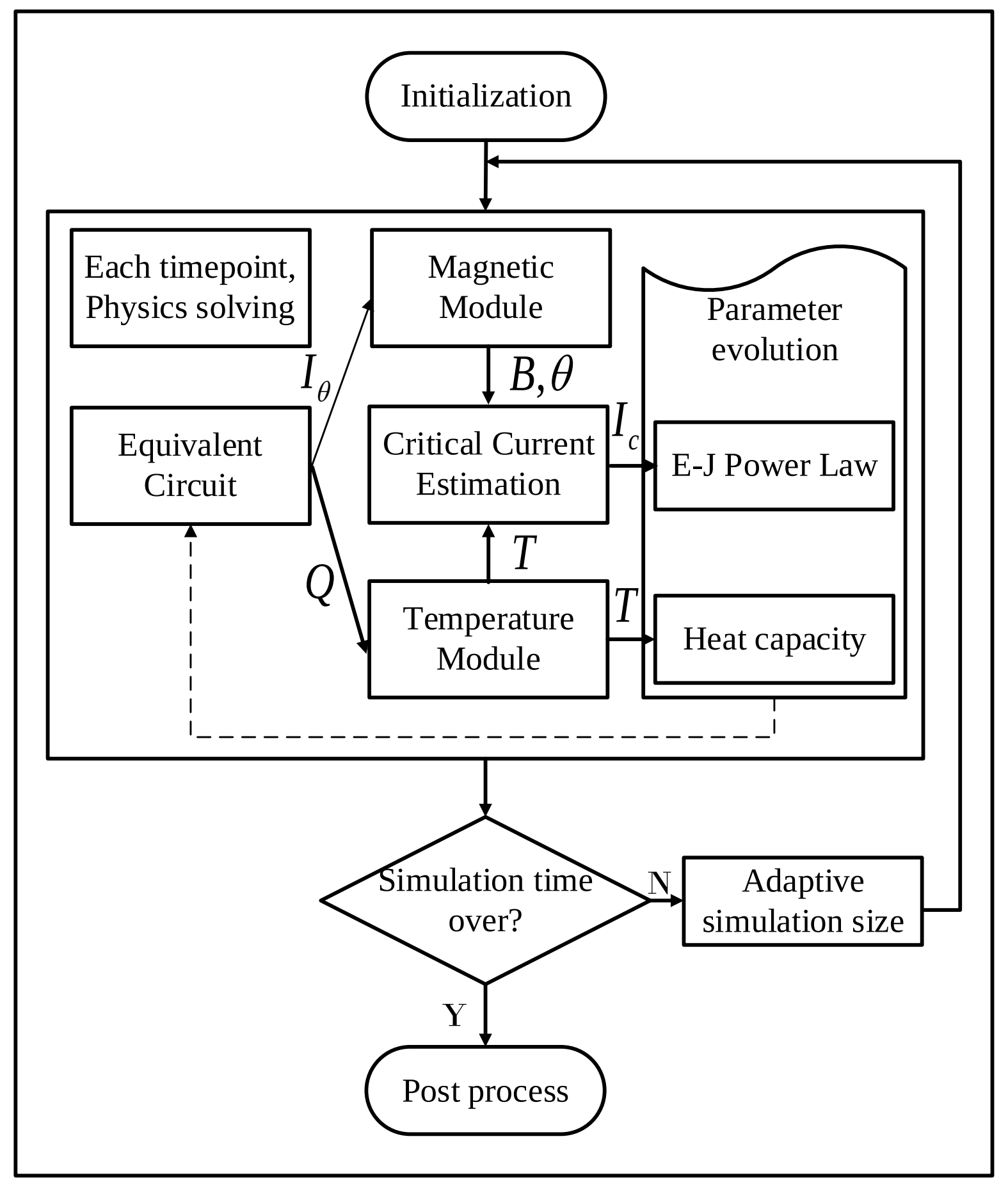
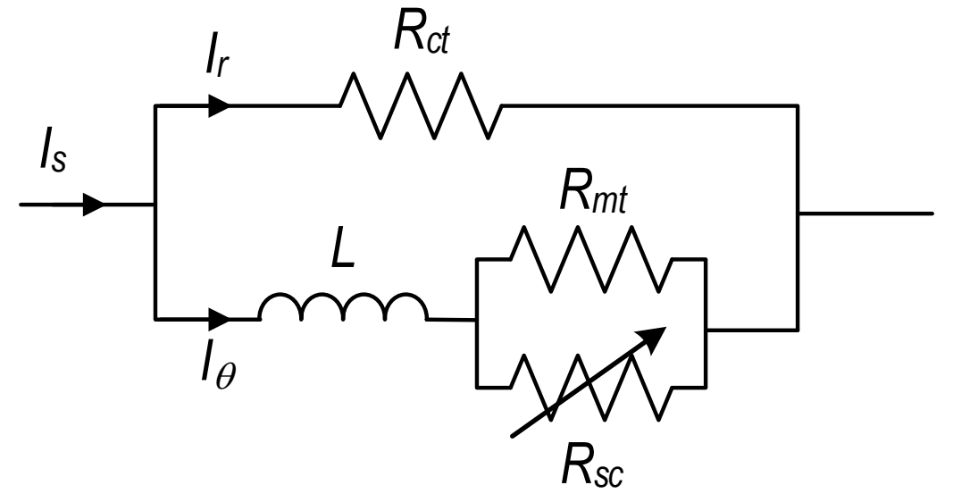


Fig. 1. Electromagnetic-thermal model flowchart for post-quench analysis. The simulation step was set to be 0.5, 0.05, and 0.002 in the linear increase phase, saturation phase, cliff-type falling phase, respectively.

Electromagnetic-thermal Model Descriptions

Equivalent Circuit - Lumped circuit model



$$L\frac{dI_\theta}{dt}+\frac{R_{sc}R_{mt}(T)}{R_{sc}+R_{mt}(T)}I_\theta = R_{ct}(I_s - I_\theta)$$

- ✓ L: inductance of the coil
- ✓ R_{ct}: contact resistance
- ✓ R_{mt}: martirix resistance
- ✓ R_{sc}: REBCO layer resistance

Fig. 2. Lumped equivalent circuit model of NI pancake

Thermal module – Lumped-capacitance thermal model

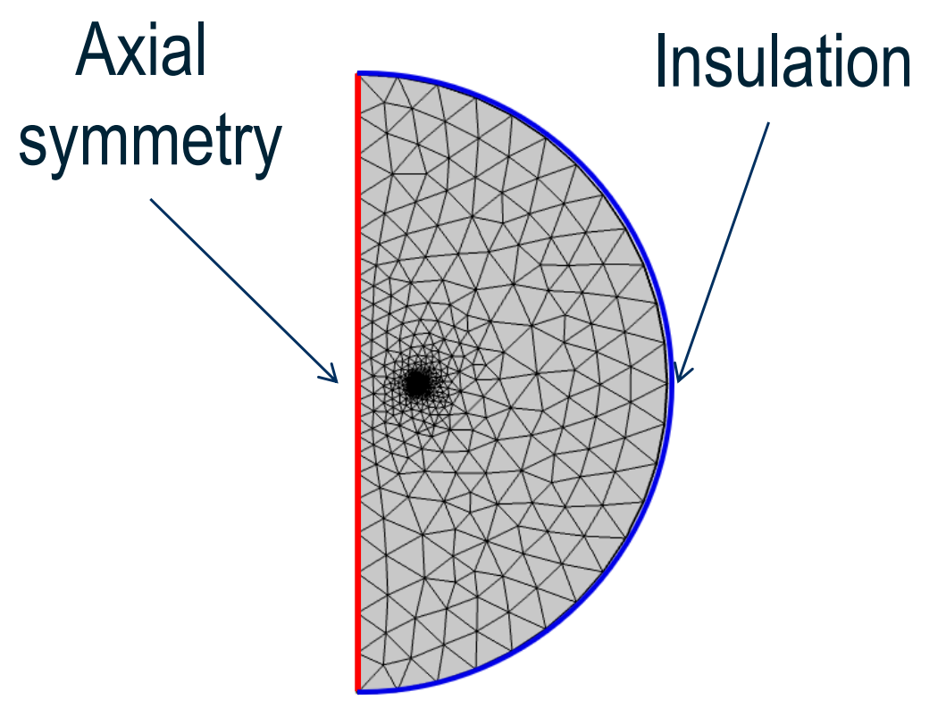
$$\rho C_\rho(T)\frac{dT}{dt} = Q(t) + \boxed{k(T)\nabla^2 T} + \boxed{h(T)(T-T_\infty)\frac{P}{A}}$$

- ✓ ρ : mass density
- ✓ $C_\rho(T)$: heat capacity
- ✓ $Q(t)$: joule heating
- ✓ k: thermal conductivity

- The second and third terms on the right-hand side stand for heat conduction within the coil and convective transfer into the cryogen, respectively. The thermal conduction across the coil was ignored and adiabatic condition was considered [2].

Electromagnetic module – Combined simulation between COMSOL and MATLAB

- In each time point, the calculated operating current I_θ was calculated by MATLAB and transferred to COMSOL, and the corresponding field distribution was computed for critical current estimation.



Maxwell's formulas

$$\nabla\times\boldsymbol{H} = \boldsymbol{J}$$

$$\boldsymbol{B} = \nabla\times\boldsymbol{A}$$

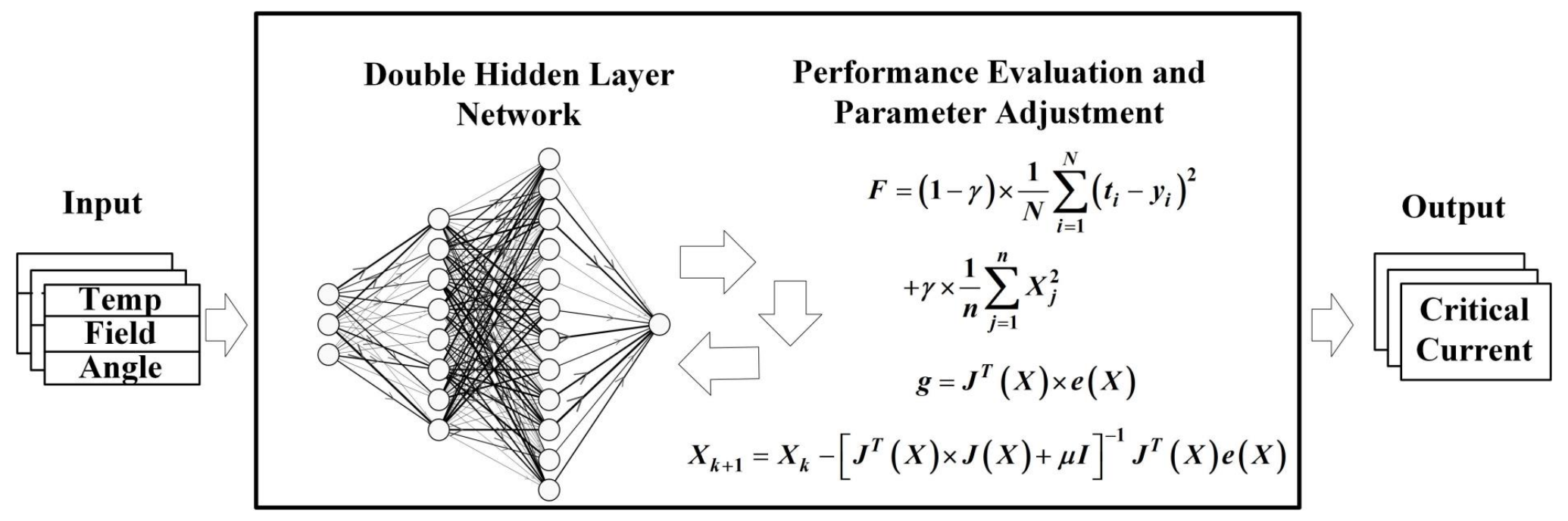
$$\boldsymbol{J} = \sigma\boldsymbol{E} + \boldsymbol{J_e}$$

$$|\boldsymbol{J_e}| = \frac{N_t I_\theta}{A_s}$$

Fig. 3. FEM model mesh

Temperature-field-angle critical current estimation module

- The temperature-field-angle dependent critical current was estimated by a double hidden layer Bayesian regularized neural network [3].
- The average critical current was estimated on the pancake, where a fixed multiplier factor of 1.25 was used for corresponding experiment data.



$$F=(1-\gamma)\times\frac{1}{N}\sum_{i=1}^{N}(t_i-y_i)^2+\gamma\times\frac{1}{n}\sum_{j=1}^{n}X_j^2$$

$$g=J^T(X)\times e(X)$$

$$X_{k+1}=X_k-\left[J^T(X)\times J(X)+\mu I\right]^{-1}J^T(X)e(X)$$

Fig. 4. Temperature-field-angle critical current estimation structure of double layer Bayesian regularized neural network

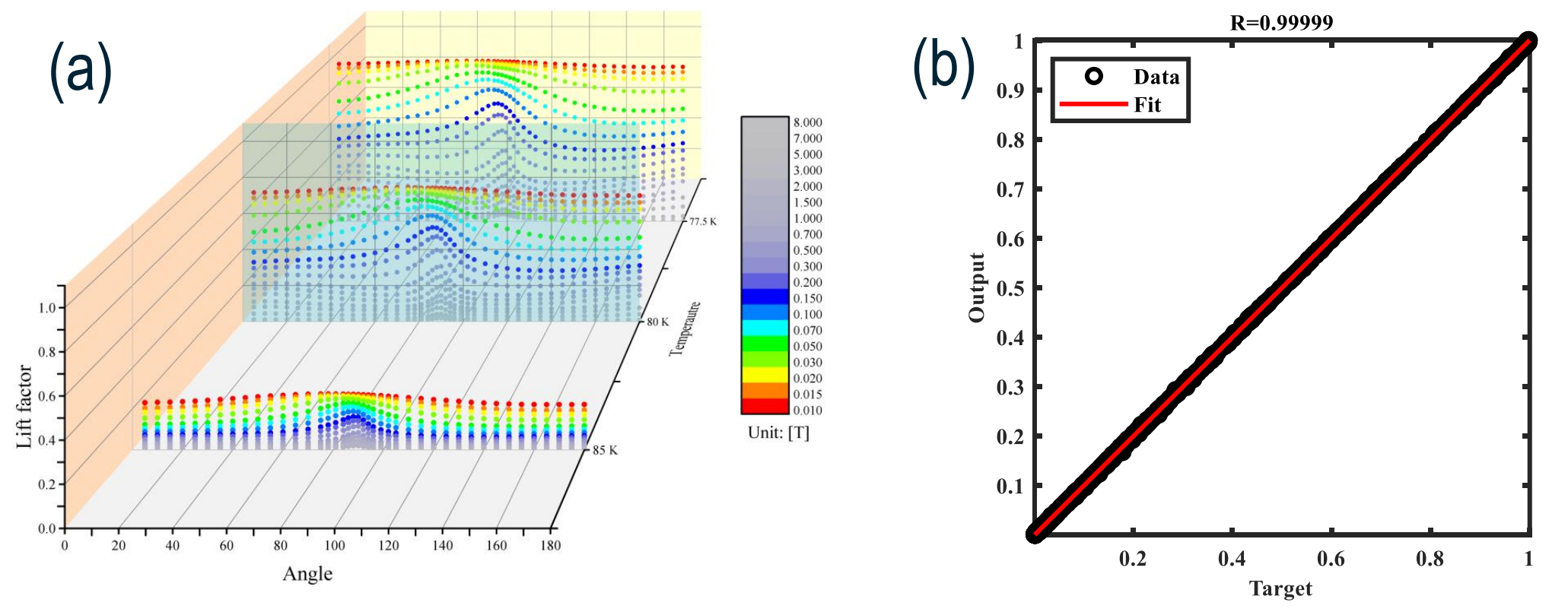


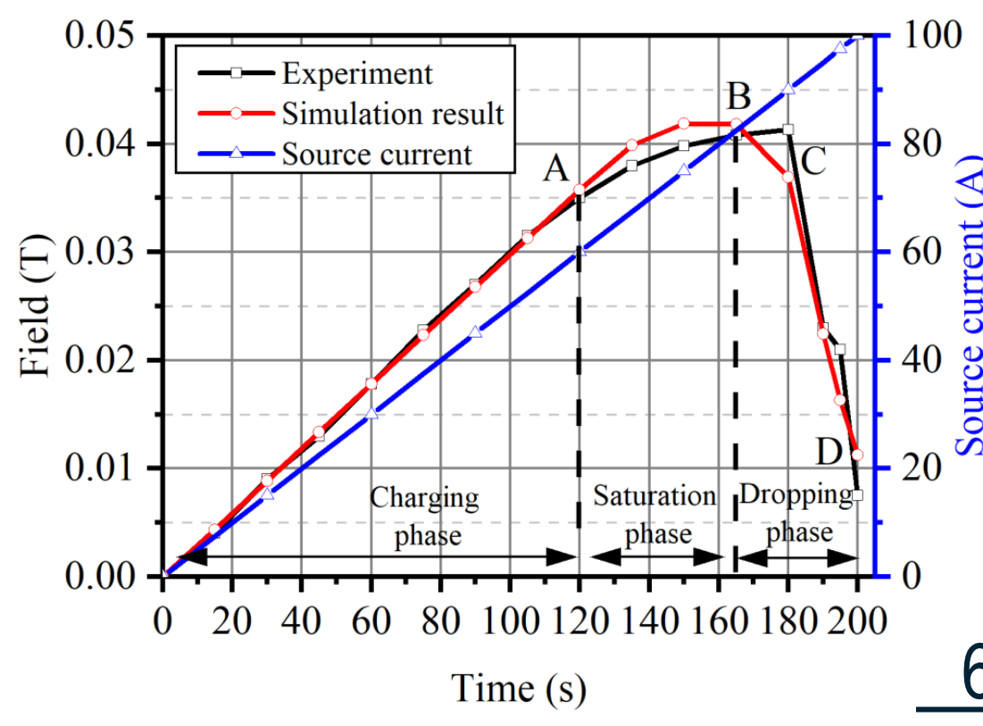
Fig. 5. (a) Experiment data including 77.5 K, 80 K, and 85 K data group lift factor, totally 2226 experiment data points. (b) Cross-validation with linear regression result of experiment target data and prediction output from BP neural network.

Case Study -- Coil Parameters

TABLE Ⅰ
PARAMETERS OF THE NI TEST COIL FOR "OVER-CURRENT" TEST AND SIMULATION

Tape Parameters		
Manufacturer		Super Power SCS4050
Tape width	[mm]	4.0
Tape thickness	[mm]	0.1
Copper stabilizer thickness	[mm]	0.04
Ic, 77 K, self field	[A]	85
Ic, 77 K, coil	[A]	63
Magnet Configurations		
Inner/outer diameter	[mm]	60/ 66
Overall height	[mm]	4.0
Number of turns		30
Operation		
Coil constant	[Gauss/ A]	6.0
Charging speed	[A/ s]	0.5
Inductance	[μH]	110.0
Contact resistivity, R_{ct}	[$\mu\Omega\cdot cm^2$]	70
Cryogenic		LN_2

Case Study -- Simulation Results



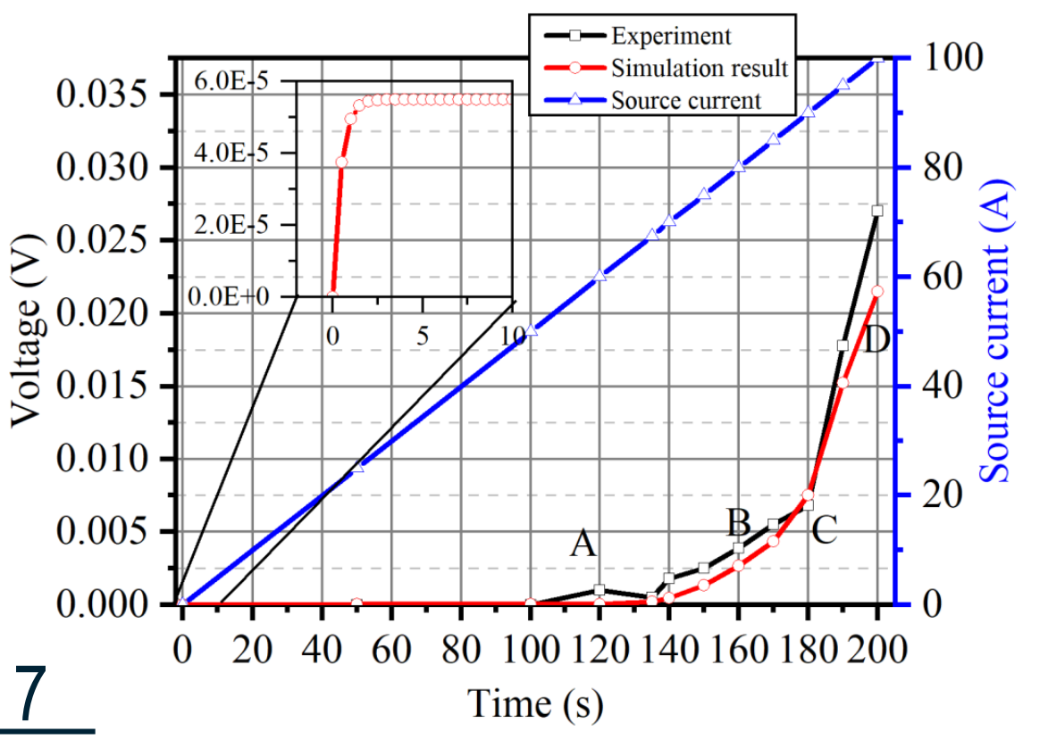


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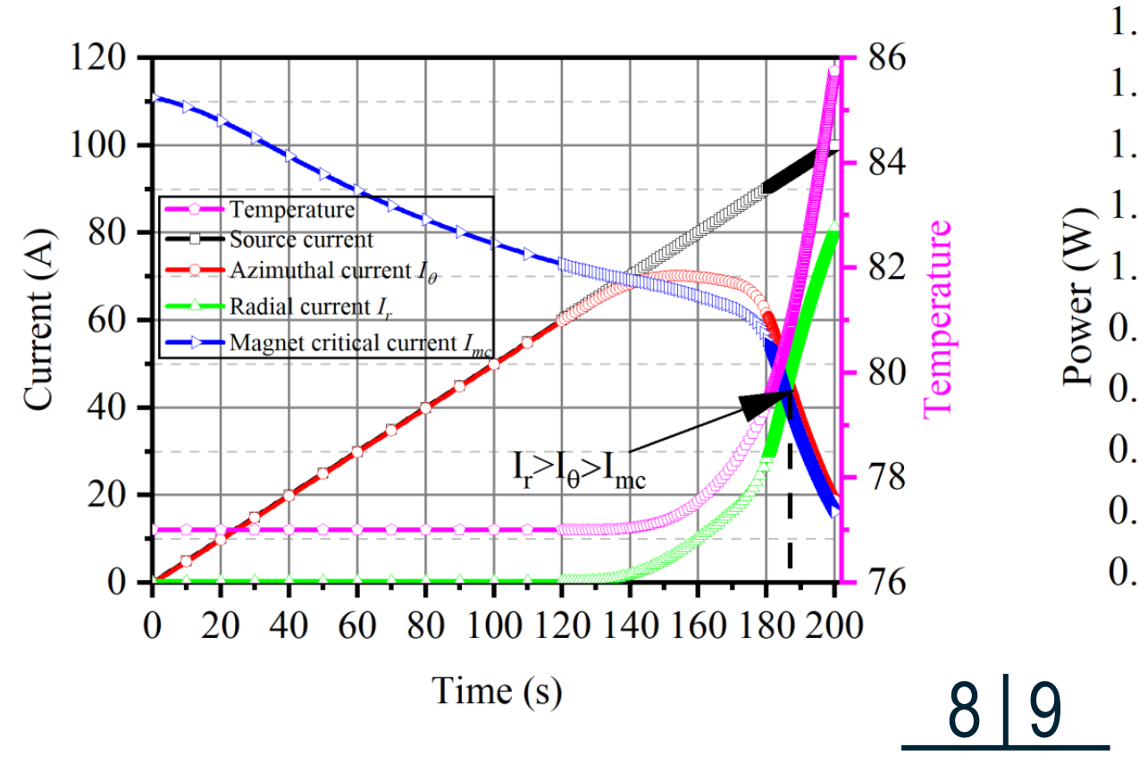
Fig. 6. Center field comparison between experiment data and simulated results. According to the simulation, the center field begins to saturate at approximately 120.0 s (at point A), starts to decrease at 162.5 s (at point B), and drops quickly from 180s (at point C) until the end of the simulation at 200 s (at point C).

Fig. 7. Terminal voltages comparison between experiment data and simulated result. (a) The black rectangular line data from an inverse calculation based on experiment results [4]. (b) According to the simulation, the inductive voltage is 5.49E-5 V. (c) The terminal voltage starts to increase from point A, slowly rises to point B, and then rapidly increases from point C until simulation ends at point D.



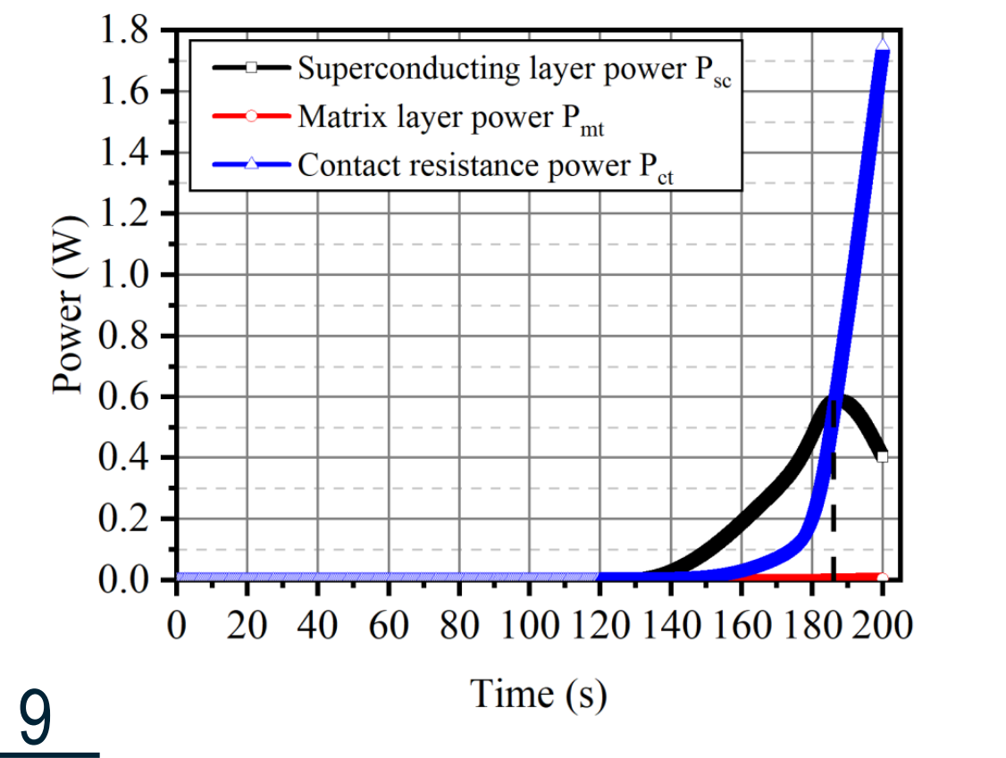


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Fig. 8. Simulated result of current and temperature profile. Before t = 120 s, the magnet critical current decreases as increasing azimuthal current I_θ. From t = 120 s to t = 162.5 s, azimuthal current further increase to saturation and temperature start to rise, hence the magnet critical current further decrease. From t = 162.5 s to 180 s, the azimuthal current slowly decreases and approaches the magnet critical current, where magnet critical current decrease due to temperature increase. From t = 180 s, the azimuthal current drops with magnet critical current at a similar rate until the end of the simulation at 200 s. The descent rate is mainly determined by temperature-field-angle dependent critical current decay rate. At time 186.2 s, the radial current I_r starts to be greater than the azimuthal current I_θ.

Fig. 9. Each component power profile during the entire simulation process. (a) The power was mainly produced by superconducting layer and contact resistance. (b) The contact resistance power is greater than superconducting power when $I_r > I_\theta$, around 186.2 s.

Case Study -- Sudden Discharging Simulation

- From the analyses of the over-current behaviors, a cut-off voltage could be determined by:

$$V_{cut} = R_{ct} * i_{cut\_r}$$

where i_{cut_r} is the radial current, which is the value greater than both the azimuthal current and the coil critical current for the first time.

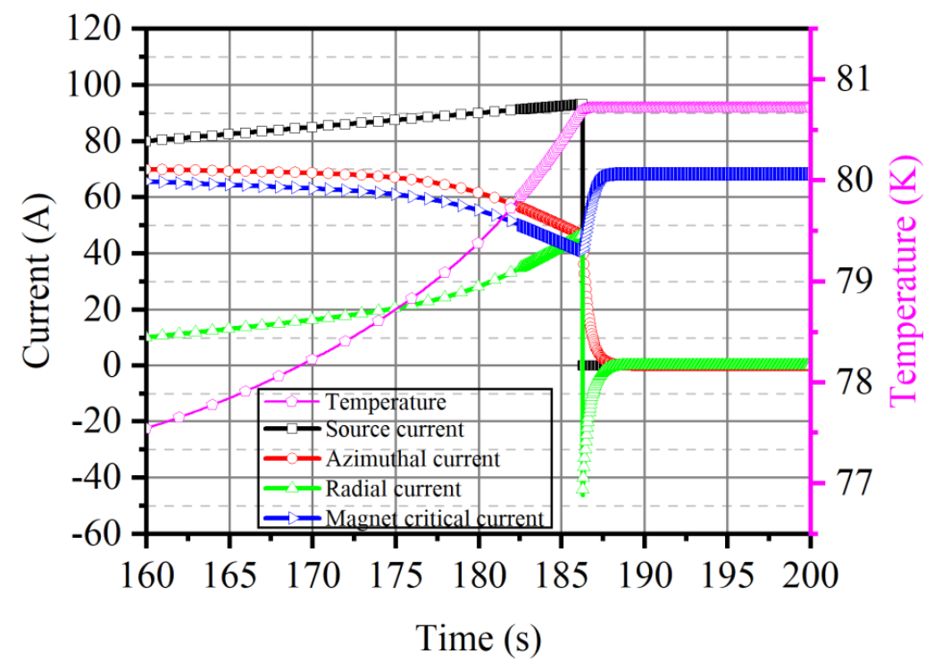

Fig. 10. Simulated result of current and temperature profile with the sudden-discharging operation. (a) Temperature rises 0.3 K after sudden-discharging. (b) Magnet critical current rises first and then maintains a stable value.

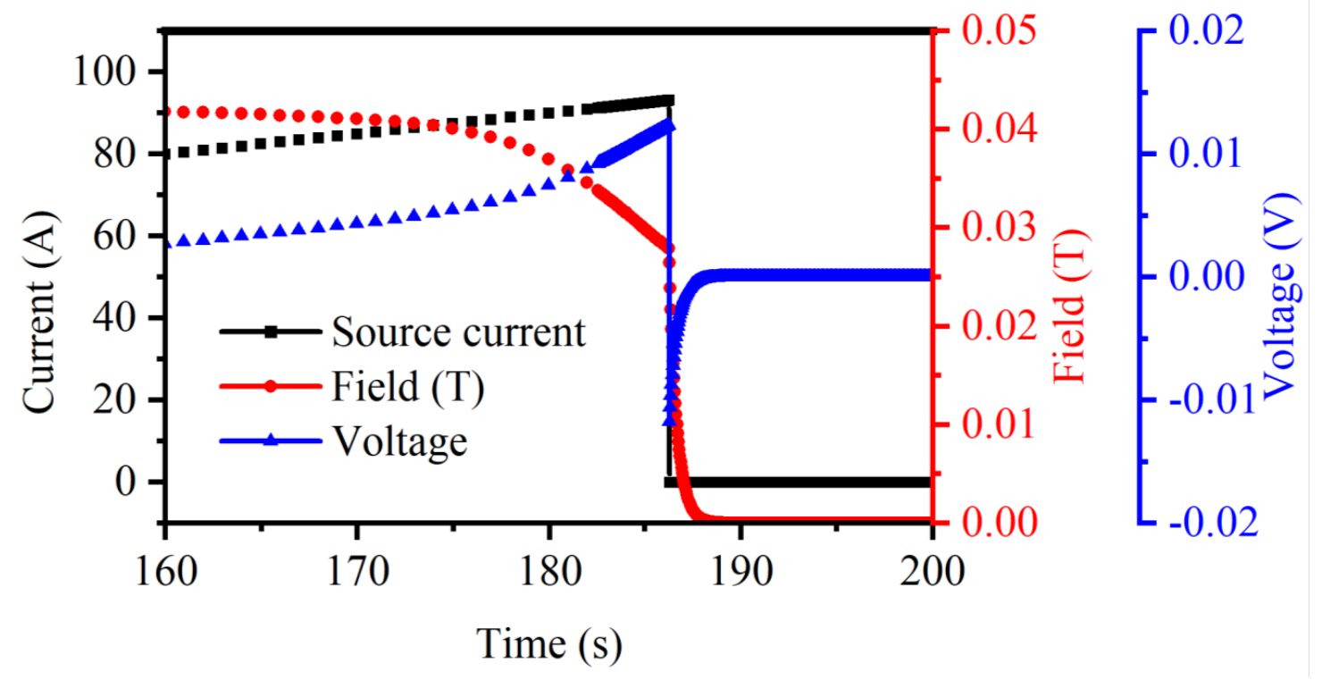

Fig. 11. Simulated result of center field and terminal voltage.

Conclusion

- An electromagnetic-thermal model was developed and validated to analyze pancake post-quench behavior, including sudden-discharging operation, where a temperature-field-angle critical current estimation model was used.
- Summarizing the simulation result, when the azimuthal current is greater than the magnet critical current, it will gradually saturate and approach the magnet critical current, and then decrease at a similar rate.

Reference

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[3] Q. Liu and S. Kim. "Temperature-Field-Angle Dependent Critical Current Estimation of Commercial Second Generation High Temperature Superconducting Conductor using Double Hidden Layer Bayesian Regularized Neural Network," Submitted to *Supercon. Sci. Technol.*
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