Comparison of 2D simulation models to estimate critical current of a superconducting coil

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Motivation

- Review available numerical models of superconducting (SC) coils
- Compare results of simulations and measurement in the case of a SC coil with more than 200 turns
- Provide readers with a general idea on how to estimate critical current of a SC coils for power devices

Model theory

H-formulation
\[ \mathbf{V} \times \mathbf{H} = \mathbf{J} \]
\[ \mathbf{V} \times (\mathbf{V} \times \mathbf{A}) = -\mu_0 \mathbf{J} \]

- The governing equations of H-formulation are Ampère’s law and Faraday’s law and state variable is magnetic field \( \mathbf{H} \) [1][2]

T-A formulation
\[ \mathbf{V} \times (\mathbf{V} \times \mathbf{A}) = -\frac{\partial (\mathbf{V} \times \mathbf{A})}{\partial t} \]
\[ \mathbf{V} \times \mathbf{A} = \mathbf{J} \]

- T-A formulation is based on thin strip approximation and two state variables: current vector potential \( \mathbf{T} \) in SC layers and magnetic vector potential \( \mathbf{A} \) in the whole area [3]

P-model
\[ \mathbf{J} = \mathbf{J} (\mathbf{B}, \mathbf{J}) \]
\[ \mathbf{V} \times (\mathbf{V} \times \mathbf{A}) = \mathbf{J} \]

- The so called P-model is based on the asymptotic limit of Faraday’s equation when \( t \) approaches to infinity [4]

Load-line method
\[ \mathbf{V} \times \mathbf{A} = \frac{\mu_0}{\mathbf{H}} \]

- The load-line method is implemented by calculating the magnetic field at a give current and by comparing it to the expected critical current of the tape at that field [5]

Experiment

Coil specification

- A-A
- Copper plate
- Top SC coil
- Insulation
- Top SC coil
- Coil former
- Bottom SC coil

Critical current of the SC coil

- Critical current: 43.2 A by LN₂, 42.3 A by cond.
- n-value: 22.1 by LN₂, 32.5 by cond.
- Top coil reaches determined the critical current

Discussion

Possible reasons to the deviation

- Simulations use a fixed n-value, while in reality n-value changes with the magnetic field
- Uniformity of the tape \( I_c \) along length (± 20%)
- Length uniformity of the angular dependence of the superconductor (0.3%-6.7%)
- Manufacturing process of the superconducting coil

Due to above mentioned reasons, the coil has a lower \( I_c \) than expected based on the short sample measurement.

Conclusion

The load-line method gives better result to experiment, not because it explains what happens in the superconductor, but because uniform current density assumption gives lower \( I_c \) estimation. If ideal tapes are used, the other three models could give better results.

References


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Anisotropy of tape

Note: The lift factor is defined as the ratio of the critical current at a specific field to the critical current at 77 K with self field

Critical current of the SC coil

Note: Cond.-mes., LN₂ represents conduction cooling and liquid nitrogen at 77 K (0.1 µV/cm criterion as an example)

Magnetic field distribution at operation current of 51 A and n-value of 30 (below critical current with criterion 1 µV/cm)

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