Tool Chain for Simulations of Bi-Filar Coil Winding for Fast Quench Protection

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1. Background

Superconducting magnets used in accelerators necessarily operate very near their critical temperature Tc. Small excursions in operating conditions can lead to a "quench" event where it loses its super conducting ability and becomes purely resistive, leading to material failure. Active control schemes like coupling-loss-induced quench (CLIQ[1]) can be used to mitigate this. However, CLIQ's response time is in the millisecond scale and order of magnitude improvements are needed for higher field next generation accelerator magnets.

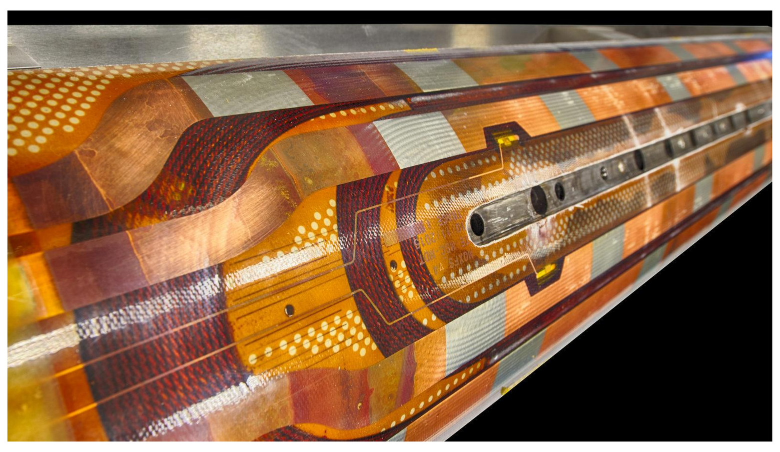

Fig. 1 Accelerator Magnet

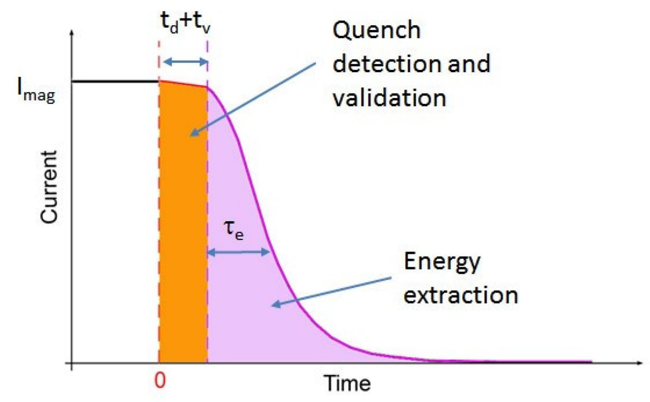

Fig. 2 Current Response to Quench Protection

2. Overview

Bi-filar[2] coil winding can potentially respond faster than CLIQ. It's based on a bifilar-wound coil that runs in series during normal operation, then switches to anti-parallel after a quench (Fig. 3). This is a developing toolchain aimed at enabling the prototyping of bifilar quench protection systems through automated circuit generation and parameter sweeps.

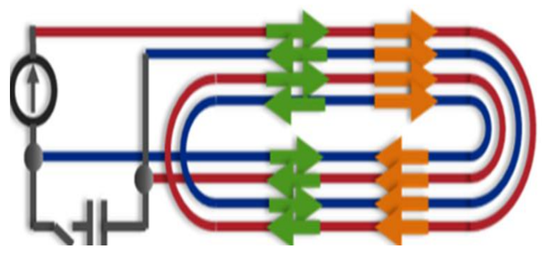

Fig. 3 Bi-filar Coil

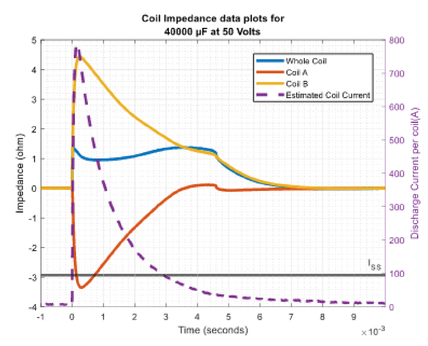

Fig. 4 Prototype test in nitrogen

3. Toolchain

A generalized Python/LTSpice framework for prototyping bifilar quench protection systems. It accounts for SC tape properties, magnet geometry, and mutual coupling, then sweeps across capacitor and voltage ranges over a defined time. Output is a 3D surface of dissipated energy (E) vs. capacitance (C) and voltage (Vc), aiding design optimization.

Inputs

- SC Tape Dimensions
- SC Materials
- Critical Current/ Temperature Curve

Outputs

- Plot of System Energy as a function of Voltage on the capacitor and Capacitance

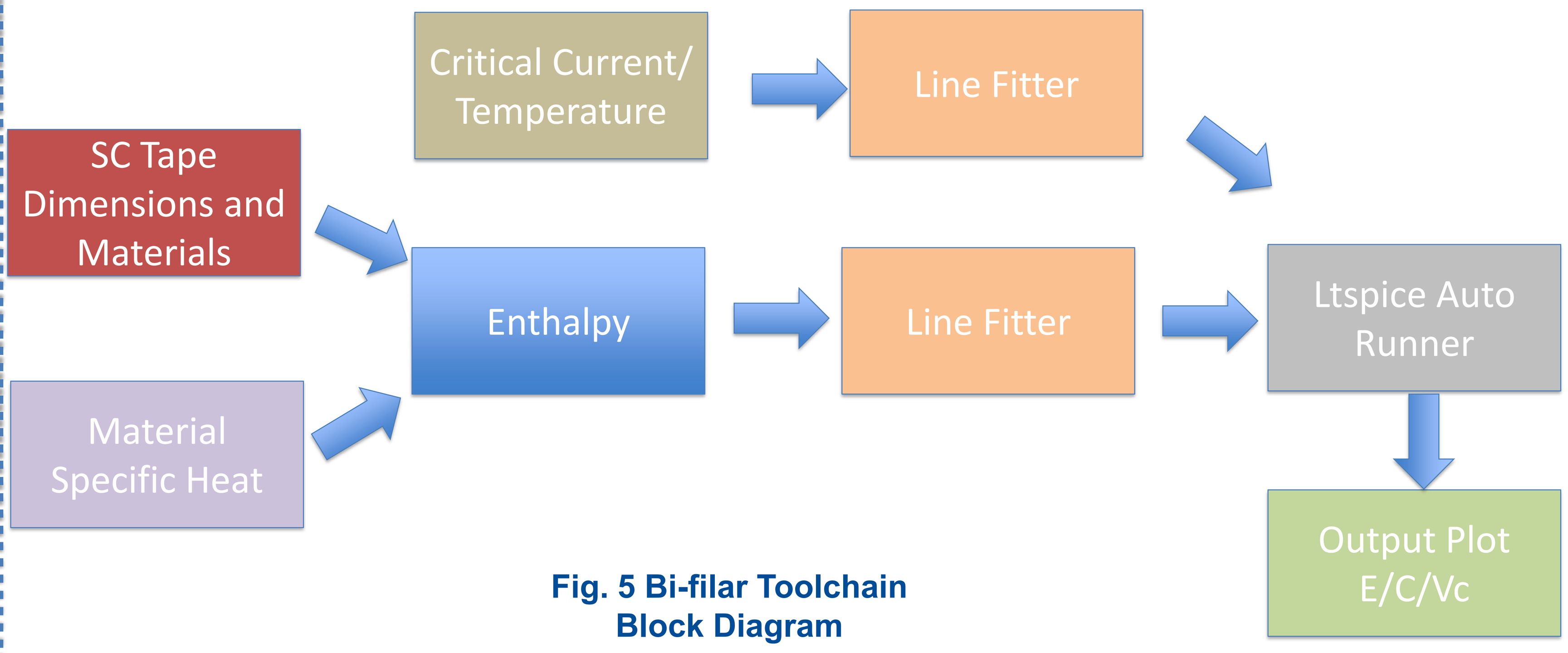

Fig. 5 Bi-filar Toolchain Block Diagram

4. Spice Editor

Once the program absorbs the necessary data it will:

- Update netlist with new functions
- Run the sim silently
- Extract and plot necessary data(E/C/Vc)

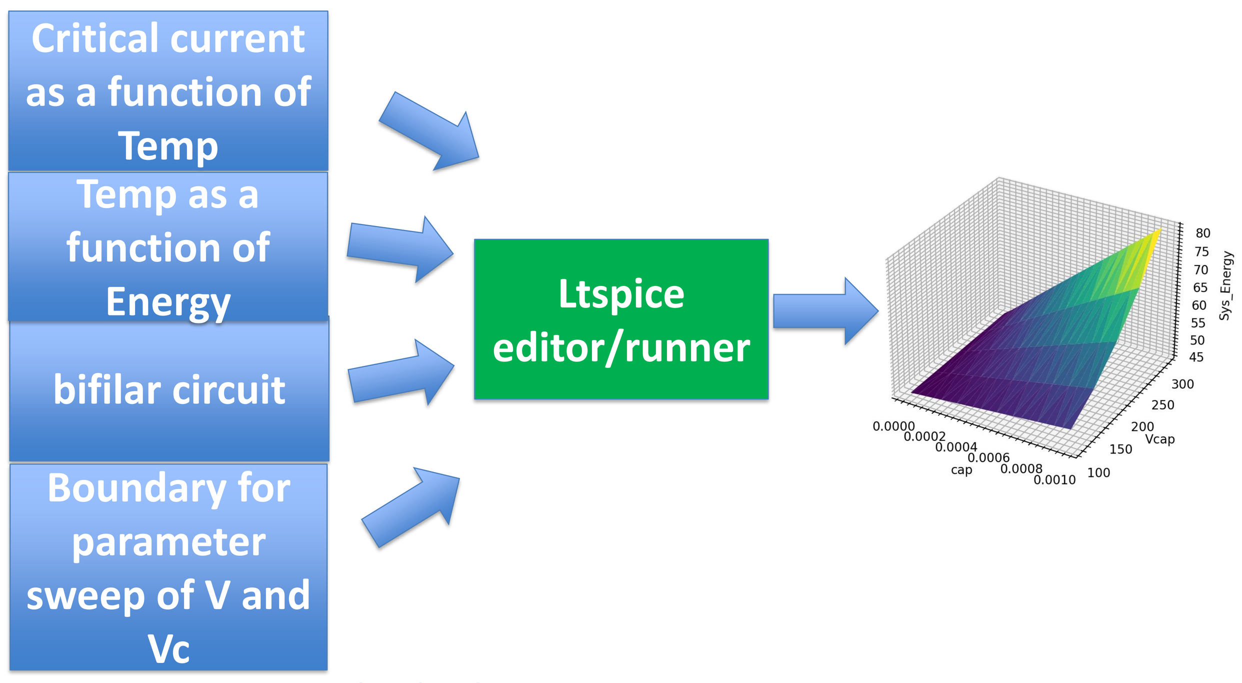

Fig. 6 SPICE Simulation Block Diagram

4.1 Circuit

LTSpice circuit model of the bifilar setup with coupled inductors, inactive voltage sources for current measurement, and dynamic resistance models representing the superconductor. All component values are parameterized, allowing Python to dynamically modify the circuit based on the user-defined magnet design.

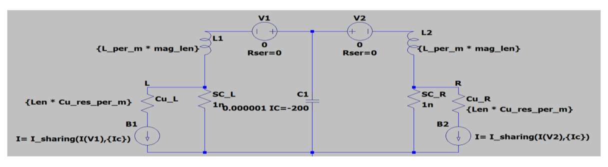

Fig. 7 Bi-filar Circuit Schematic

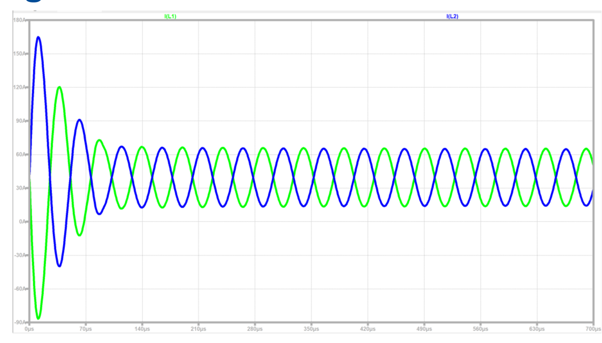

Fig. 8 Bi-filar Circuit Current Response

4.2 Dynamic Resistance

LtSpice Circuit showcasing the current sharing capability of this dynamic resistance model.

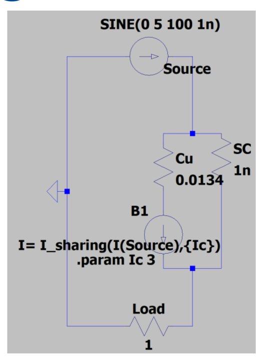

Fig. 9 Dynamic Resistance Schematic

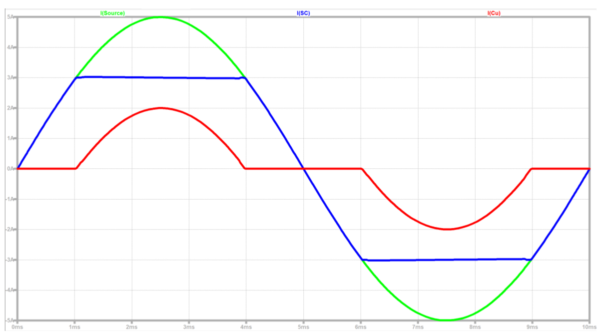

Fig. 10 Dynamic Resistance Model with Current Sharing

4.3 Multiphysics in LTSpice

To ensure modeling accuracy and due quenches being innately Multiphysics problems, behavioral sources were used to emulate thermal feedback

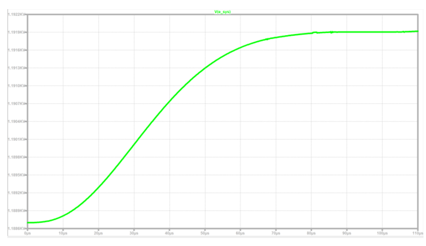

Fig. 11 Energy Generated from current

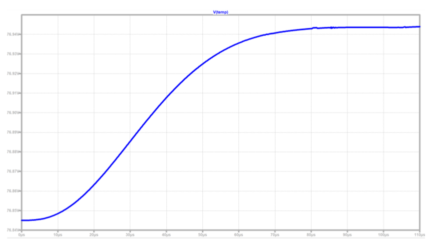

Fig. 12 Temperature rise

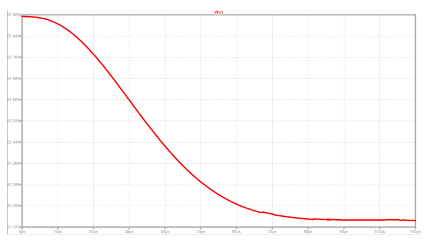

Fig.13 Critical current degradation

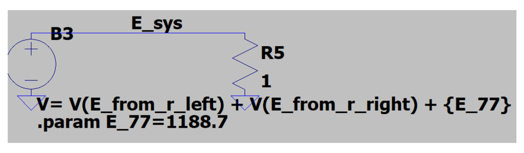

Fig. 14 Behavioral Source Used To Model Energy accumulation

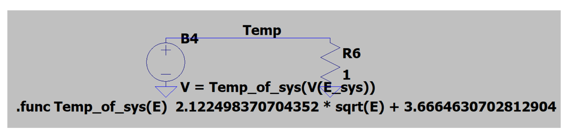

Fig. 15 Behavioral Source Used To Model increase in temperature

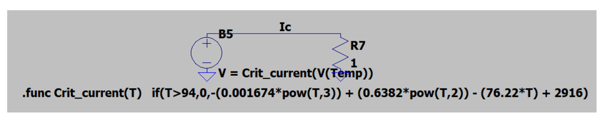

Fig. 16 Behavioral Source Used To Model Critical Current degradation

5. Conclusion

This work is ongoing and aims to fully validate the proposed model. Once complete, it can be developed into a comprehensive tool to assist in designing bifilar coils for magnets of any geometry and using any type of superconductor.

6. References

1. E. Ravaioli, V. I. Datskov, G. Kirby, H. H. J. ten Kate, and A. P. Verweij, *Quench Protection of Superconducting Magnets*, CERN, Geneva, Switzerland, CERN-2014-005, Apr. 2014. [Online]. Available: https://cds.cern.ch/record/1695142
2. S. T. Krave and V. Marinozzi, "Bi-Filar Coil Winding for Fast Quench Protection," *IEEE Trans. Appl. Supercond.*, vol. 34, no. 5, Art. no. 4704506, Aug. 2024. [Online]. Available: https://doi.org/10.1109/TASC.2024.3370099

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