Bi-Filar Coil Winding for Fast Quench Protection

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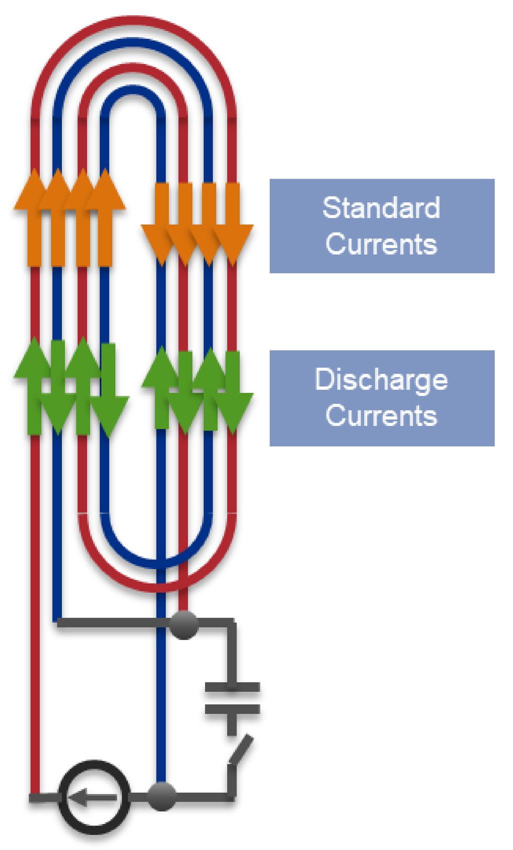
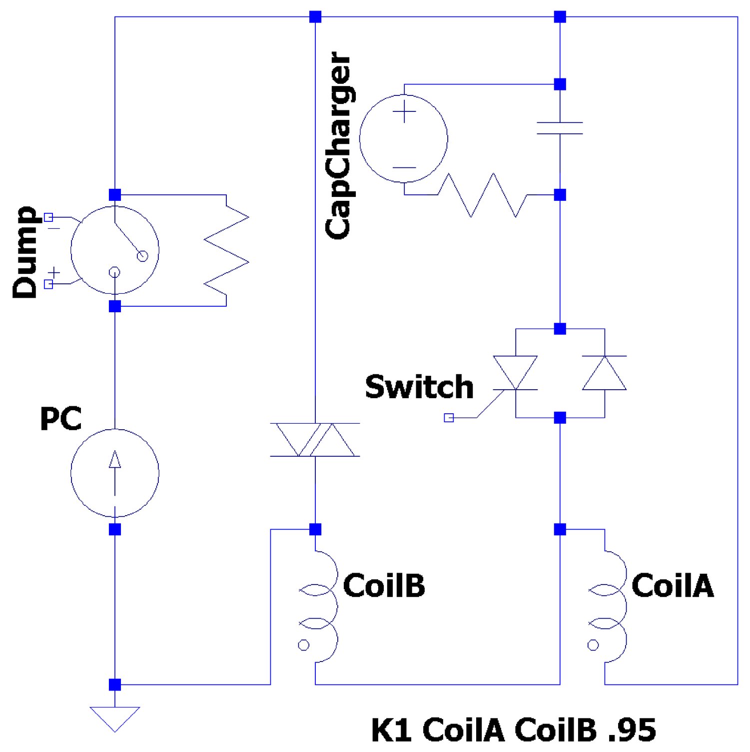
Abstract

As superconducting magnet technology is pushed towards higher performance, energy density and total stored energy follow exponentially. Protecting magnets becomes substantially more challenging with traditional methods being stretched to their limits. New technologies such as CLIQ promise to provide a robust method to protect advanced magnets, however they become inductance limited in large magnet strings or at low field, leading to more complex configurations. A technique to substantially reduce this limitation and improve response time is presented, by winding a coil in a bifilar fashion. This allows for extremely high di/dt. The concept is then demonstrated on a small REBCO coil.

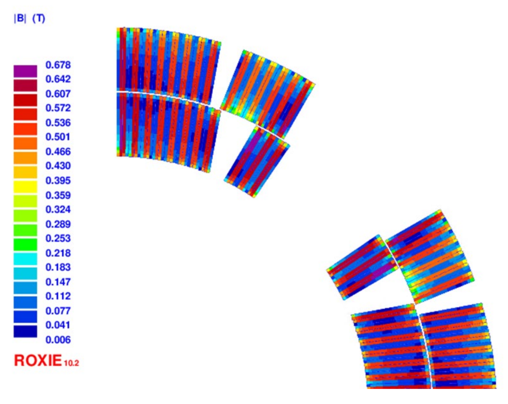


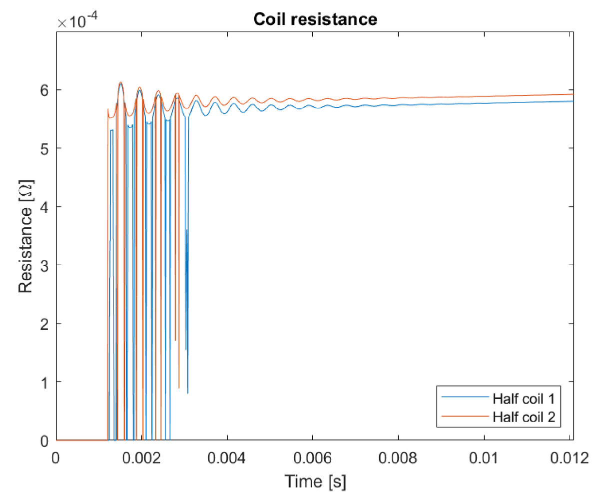
Cartoon of coil illustrating current flow in normal operation and opposing currents in quasi-zero-inductance mode.



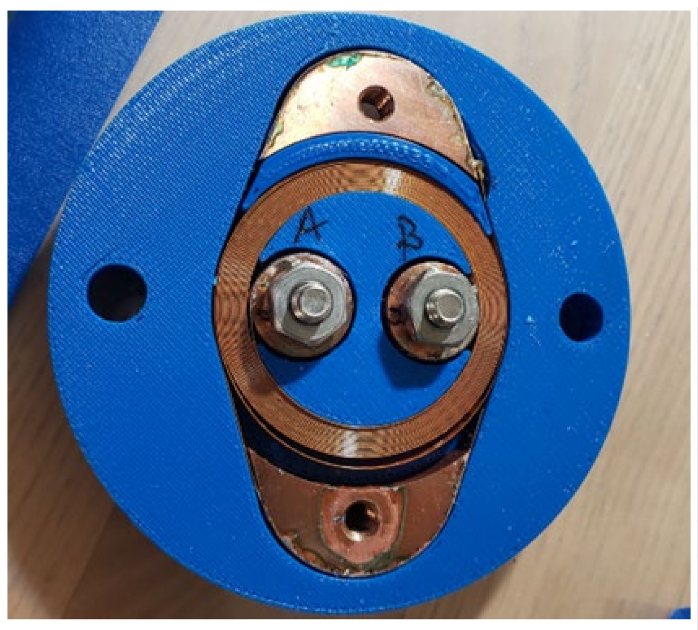
Equivalent circuit approximation. Note that this is nearly electrically the same as CLIQ, with the addition of a high coupling coefficient between coils.

This concept can be expanded to existing cross sections by assuming every other turn is a different coil. Roxie has been used to find the mutual inductance between coils and this can be used to calculate a coupling coefficient to be modeled. Coupling coefficients for QXF have been used and found an effective coupling coefficient of 0.992. An example differential powering is shown below.

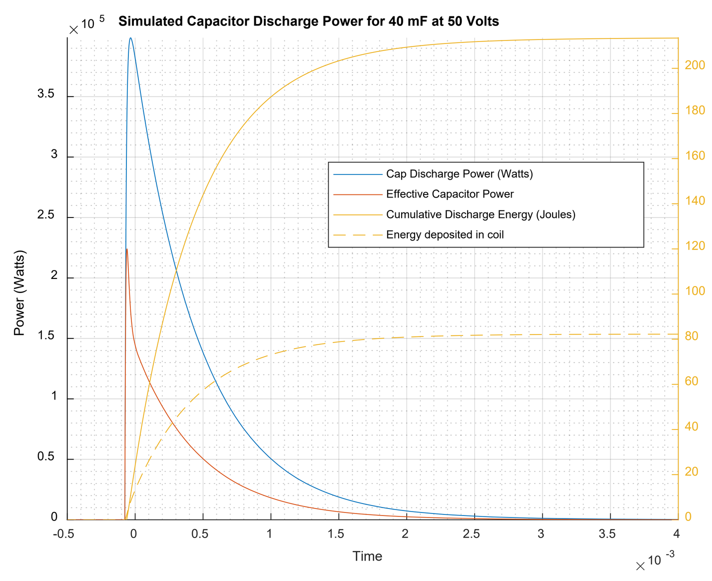




- From tight packing of turns, coupling is very good, K=0.992
- L_{eq} ~0.007 mH/m
  - Occasional errors thrown here, but has output same value with no error…
  - ~.5T at +/- 17320 A
  - 0.0144 T/kA
- LEDET simulation shows initiation of quench on 1st cycle at timescales of ~1 ms

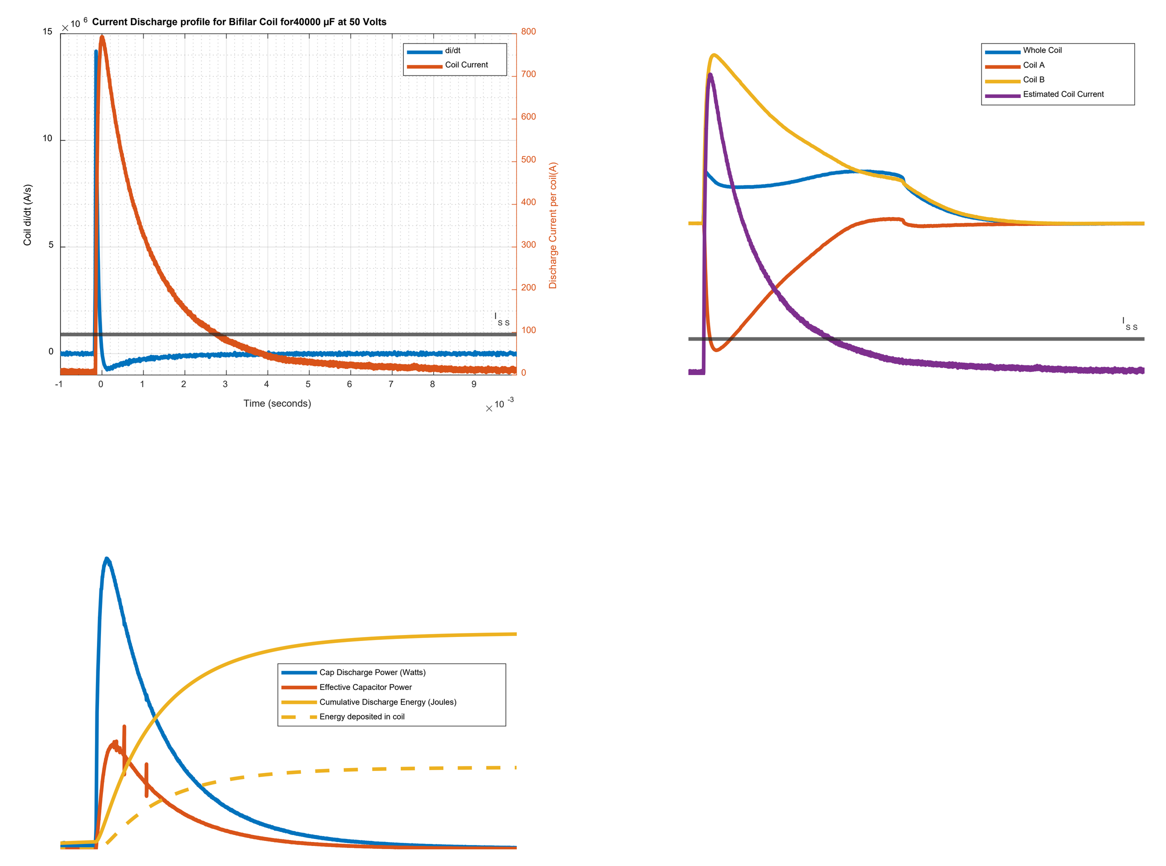


Small REBCO coil fabricated from 4mm tape with IC of ~95 A at 77 K



Coil Parameters		
N Turns (monofilar representation)		20
Inner Radius	mm	10
Insulated Conductor Thickness	mm	0.2
Insulated Conductor Width	mm	4.125
I_SS	A	95
Conductor Thickness	mm	0.1
Conductor Width	mm	4
Coil Geometry		
Outer Ideal Radius	mm	14
Outer Real Radius	mm	14.2
Coil Area	mm^2	302
Total Conductor Length	m	1.51
Magnetic Parameters		
Average Coil Radius	m	24.2E-3
Coil Thickness	m	4.0E-3
L_series (ideal)	H	22.9E-6
L_halfcoil inductance	H	5.7E-6
Coupling Coefficient		890.0E-3
M_Bifi	H	1.3E-6
Bore TF	T/A	1.3E-3
Bore Field	T	119.4E-3
Resistance Calculation		
Conductor RT Resistivity	(ohm/m)	102.0E-3
Whole Coil Resistance	ohm	153.8E-3
Copper Resstivity (RT)	ohm*m	16.8E-9
rho 77		2.1E-9
Half Coil Resistance RT		76.9E-3
Half Coil Resistance 77		9.8E-3
Powering parameters		
V0	Volts	20
C	Farad	5.00E-03
f_0 (Hz)	Hz	2.0E+3
di/dt 0v		15.9E+6
iMax_Ind		1.3E+3
ImAX Resistive		4.1E+3
Skin Depth		653.0E-12

A small coil made from REBCO tape has been fabricated and tested in LN2. Modeling and real work testing show that the calculated differential mode inductance matches the real world values, leading to the ability to transfer tens of kW of power at minimal voltages at di/dt in the 10's of MA/s both in the small coil, as well as ROXIE modeled cases.



Measured data for high capacitance discharge, transferring 12 joules to the coil in ~5ms

Conclusions and Next Steps

Bifilar winding offers an interesting way to optimize existing technologies such as CLIQ, with minimal additional overhead. The technique has been implemented on a small REBCO solenoid and demonstrates the validity of a simple LC circuit model with coupled inductors to the overall electrical behavior of the circuit. Currents can easily be driven at potentially several MA/s with a large energy transfer efficiency and show the potential to use this method for fast quench protection in superconducting magnets.

The small pancake will be tested to better understand the onset of the normal transition, likely at substantially higher operating currents to develop a stable quench.

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