The Effect of Shorted Secondary Material on Quench Protection of an HTS Tape Solenoid discharged across a Varistor

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Abstract: Studies suggest that an insulated ReBCO tape solenoid coil that is well-coupled inductively to shorted secondary can effectively be quench protected by discharging the coil across a constant voltage resistor. The discharge voltage across the constant voltage resistor is much lower than it would be for a constant resistance resistor that is used to achieve the same final quench temperature with or without a shorted secondary. How this quench protection works, depends on the constant voltage resistor characteristics, the properties of the shorted secondary circuit material and the amount of the material in the circuit. A previous paper suggests that the RRR shorted secondary circuit material is not important, which means that aluminum can be used in the secondary circuit and structural aluminum can support both the coil and the secondary circuit when that aluminum is on the outside of a solenoidal coil.

Introduction

HTS conductors have nagging problems that make them difficult to use in superconducting magnets. These are:

1. HTS conductors are not ductile or strong like Nb-Ti.
2. The critical current of an HTS conductor is sensitive to stain in the same way A-15 conductors are.
3. Some HTS conductors must be wound and then reacted in an oxygen atmosphere. This means that Cu can't be added to the conductor and the cost of magnet fabrication is more expensive. ReBCO tape are not reacted, so they can have Cu in them.
4. The specific heat of materials in a magnet goes up as temperature to the 3rd power. This means quenches propagate slowly and heat transfer time constants are much longer than for coils at 4 K.
5. Tape conductors are anisotropic in J_c, B_c, and T_c.
6. Persistent HTS joints are difficult to make.
7. HTS conductors are expensive and good cryostats are needed.

The Basic Quench Protection Problems

There are two fundamental equations that govern quench protections. The first is;

$$E_0 J_0^2 = \frac{\Gamma}{2} f F^*(T_{HS}) V_0 I_0,$$

where E_0 is the magnet stored energy, J_0 is the conductor current density when fully charged, I_0 is the current when fully charged, V_0 is the voltage across a resistor at the start of quench protection. $\Gamma = 2$ for a resistor and $\Gamma = 3$ for a perfect varistor. F* is as Follows;

$$F^*(T_{HS}) = \frac{1}{f}F(T_{HS}) = \frac{1}{f}\int_{T_0}^{T_{HS}} \left[\frac{C(T)}{\rho(T)}\right]_{LRNM} dT = \frac{1}{f}\int_0^{\infty} J(t)^2\, dt\,,$$

where C is the material volume specific heat and ρ is the material electrical resistivity.

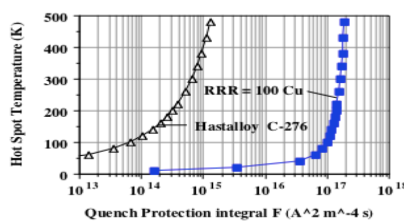

Fig. 1 Cu and Hastalloy 276 used in ReBCO wire Hot spot temperature VS F*

The voltage needed to protect a coil with a resistor is as follows;

$$V_0 = \frac{I_0 L_1}{\Gamma F(T_{HS})^*}\frac{1}{f} J_0^2.$$

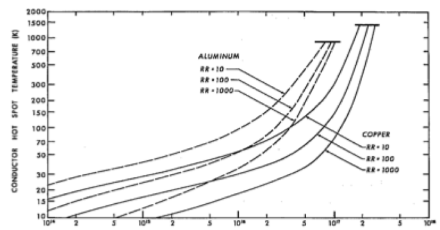

Fig. 2 Hot-spot T versus F* for various RRR Cu and Al

Superconductor and Coil Parameters

The assumed superconductor is SuperPower SCS 4050 4-mm wide tape, which carries 680 A at 20 K with only the self field in the tape, but with 2 T perpendicular to the tape the current is ~375 A.

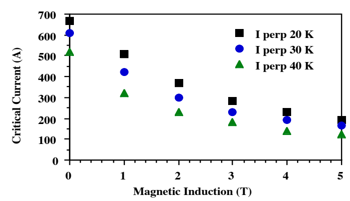

Fig. 3 Ic versus B and T with B perpendicular to the HTS Tape

Table I Basic Parameters of the HTS Magnet

Parameter	HTS-1	HTS-2
No. of Coils	2	
No. of Layers per Coil	64	
No. of Turns per layer	18	
Magnet Current (A)	307	
Ave. Coil Radius (m)	1.24	
Coil Package Length (mm)	~76	
Magnet Self Inductance (H)	76.4	
Coil Thickness (mm)	~9.1	~10.3
Conductor J (A mm^{-2})	1010	799
Copper Fraction f	0.314	0.457
Quench Velocity V_L (m s^{-1})	~0.44	~0.34
Quench Detection Time^ (s)	~0.23	~0.55
Quench Time (s)	~11	~15
Discharge Voltage V_0 (kV)	~250	~120
L_1/R_0 Time Constant (s)	~0.087	~0.18

A Quench Protection method that will Work

It is clear that discharging the coil with a resistor across the coil will not protect the coil unless the voltages across the coil are large. One must transfer the current from the coil to a shorted secondary using a constant voltage resistor (varistor) across the coil. The magnet has two coils of the HTS-2 type (in Table I) in separate cryostats. Each HTS coil has a copper shorted secondary inside and outside of the HTS coil. Both secondary windings have 288 turns of insulated copper with 25 microns of insulation on all sides. The copper secondary is 2 mm thick by 4 mm wide. The average energy in the copper after the quench is ~11 J/g. Most of the magnet energy end up in the copper with a T = ~104 K. The simulation voltage was 2 KV, and the copper RRR was 30. There was no bounce back seen in the simulation above 0.3 A, but varistor was nearly perfect.

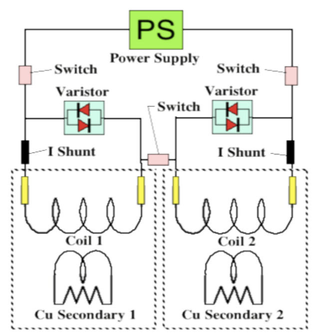

Fig. 4 Magnet Circuit used for the Quench Protection Simulation

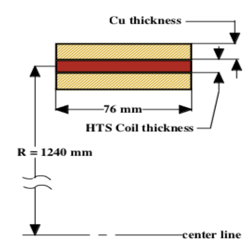

Fig. 5 HTS Coil and Shorted Secondary used for Quench Simulation

Simulation Results and Secondary Material

The varistor does cause the current to move from the coil to the closely coupled shorted secondary coils very rapidly as has been seen with large LTS magnets with a shorted secondary.

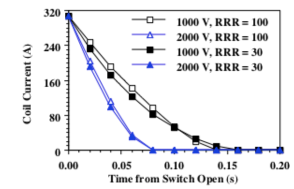

Fig. 6 The effect of Varistor Voltage and Cu RRR on Coil Current Early in the Quench Protection Process

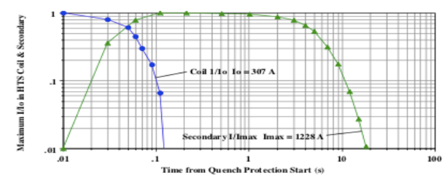

Fig. 7 The fraction of the total magnet current in the coil and Secondary Vs time

The rapid decay after the varistor is put across the coil is influenced by the varistor voltage and ε. The secondary RRR and δ have a smaller effect. The degree to which the coil current stays low is influenced by the secondary resistance over the current decay. No quench-back from the secondary is needed.

For a given secondary material mass, Al is a better choice than Cu. Since RRR makes little difference early in the quench, RRR =20 Al is like RRR = 30 Cu in resistance. Late in the quench RRR = 20 Al behaves like RRR = 40 copper at a lower temperature. The use of Al reduces the bounce-back in the middle of the quench. The value of ε affects the starting voltage V_0, but it reduces the coil conductor F* from t = 1 s to the end of the quench.

Structural Al on the outside of the secondary can carry the forces caused by the shift in the current from the coil to the secondary on the outside of the coil. The aluminum in the secondary can be tailored to reduce ε early in the quench protection process.

What appears to be a very reliable varistor from the UK has a δ of about 0.3. A factor of 100 change in the current reduces the varistor voltage a factor of 4. An Al secondary makes up for part of that. Perhaps a varistor with a lower δ can be found.

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