Various Quench Protection Methods for HTS Magnets

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HARTFORD 2019 CEC/ICMC

Abstract: **Quench protection is a major issue for high temperature superconductor (HTS) magnets that operate at high current densities with high stored magnetic energy. Quenches do not propagate rapidly in HTS coils and these coils heat up quickly because there isn't enough copper in the conductor. In addition, the conductor critical current and the engineering critical temperature will vary depending on the field orientation within the conductor. This paper points out the difference between current re-distribution within a magnet to keep a magnet from quenching and true quench protection where a portion of a coil has turned normal and the magnet stored energy is being deposited into the growing coil normal region. This paper discusses some magnet quench protection methods for both low temperature superconductor (LTS) and HTS magnets that are in the literature. A number of quench methods that work very well for LTS magnets may not work at all for an HTS magnet. The anisotropy of HTS conductors can be a limiting factor on whether a quench protection method works.**

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 and MgB_2 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 anmagnet fabrication is more expensive. ReBCO tape are not reacted, so they can have Cu in them. They can be insulated
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 protection. 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.

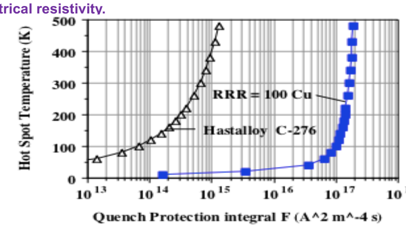

Fig. 1 Cu and Hastalloy 276 for ReBCO Wire Hot spot temperature VS F*

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

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

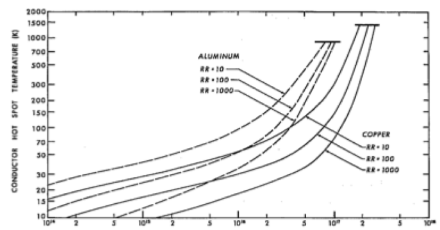

Fig. 2 Hot-spot T versus F* for various RRR Cu and Al

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. The obvious way of protecting a magnet like this from the EJ^2 in the 1st column, is to reduce the current density in the conductor by increasing *f* which reduces J by a large amount. This reduces the quench protection voltage across the resistor or varistor. One can also reduce the voltage across the coil by increasing the coil current. The table below shows the quench parameters for a magnet with SuperPower conductors that are 4 mm wide. Each layer has 18 turns. If one replaced the layer wound coil with three double pancake coils, one can increase the current to 927 A, which reduces the coil voltage by a factor of three.

Table I Parameters of the HTS magnet with three different copper thicknesses

Parameter	HTS-1	HTS-2	HTS-3
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	~12.7
Copper Thickness (μm)	20	40	80
Conductor J (A mm^{-2})	1010	799	561
Copper Fraction *f*	0.314	0.457	0.585
Quench Velocity V_L (m s^{-1})	~0.44	~0.34	~0.24
Quench Detection Time (s)	~0.23	~0.55	~1.55
Quench Time (s)	~11	~15	~20
Discharge Voltage V_0 (kV)	~250	~120	~40
L_1/R_0 Time Constant (s)	~0.087	~0.18	~0.37

A Quench Protection that works for LTS Magnets

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 or there is more copper in the conductor (See Table). Below are methods that work for Nb-Ti LTS magnets

1) Adding copper clearly is one way to go, but it is not clear that copper can be added to the conductor without causing delamination of the copper. Adding copper to BSSCO conductor is difficult after reaction. In a ReBCO tape magnet, one can wind copper strips with the uninsulated conductor. This allows the current to be shunted into the copper. A good high voltage insulation is difficult.
2) Discharging the coil through a cold resistor in series with a cold diode to heat the coil and cause the coil to quench. This method has been used in Nb-Ti and Nb_3Sn magnets. The problem with this method is the low thermal diffusivity of HTS coils at high temperatures. This is made worse when the conductor is not isotropic in Ic, Bc and Tc. The B direction with respect to the flat face of the conductor can vary within an HTS coil.
3) Quench-back from a conductive bore tube bore tube in high current density current density coils with not work because the thermal diffusion time constant to large.
4) Discharging a capacitor into the center tap of a large coil is unlikely to work because higher energy pulses are needed. The large thermal diffusion time constants is also an important factor in this quench protection method.
5) The CLIQ, which works in certain types of LTS magnet wound with cables is unlikely to work because the energy needed to quench the coil is too large.

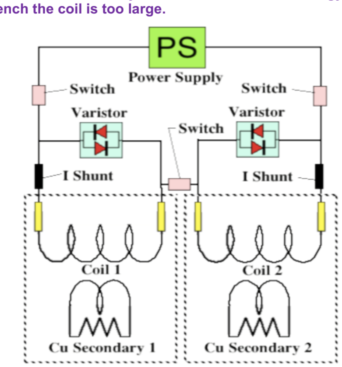

Fig. 3 Magnet Circuit used for the Quench Protection Simulation

6) The varistor can be put across the coil current leads to force the coil current into a shorted secondary (see Fig. 3). In an LTS magnet the coil current was reduced by 97 percent. This can be applied to HTS coils if they are well coupled with the low resistance secondary Circuit.

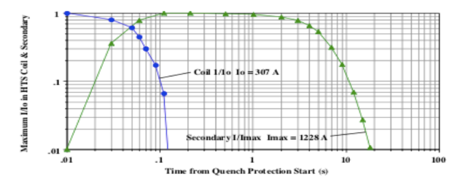

Fig. 4 The fraction of the total magnet current in the coil and Secondary Vs time

Other Methods of Quench Protection

There are other methods that have appeared in the literature that do work for protecting HTS magnets at low stored energy, but may not work for magnet circuits with high stored energies. Some of these methods are given below.

1) The no insulation method of quench protection re-distributes the magnet current as small sections of the magnet turn normal due to imperfections in the conductor. This method allows the magnet to operate up to nearly fully current. This method is fine for low stored energy magnets. This author is concerned with this method of quench protection when the stored energy is high. In early the 1960s, the no insulation method didn't protect a magnet with very little copper in the conductor during a quench. A down side of this quench protection method is that large long time-constant circulating currents can develop as the magnet is being charged or discharged. There are cases where this method can be combined with other methods of quench protection to protect a magnet.
2) A group in Japan has tested a method that used a pair of large capacitors to pump the energy out of the coil. The method worked for low stored energy coils, but this method doesn't appear to applicable for high stored energy magnets.
3) Cable in conduit coils (CICC) are a special case. A CICC magnet that is made with ReBCO conductor can have as much copper in the conductor as one wants. As a result, the current I_0 can be very large. Quench propagation in cable in conduit conductors is driven in part by the heating of the gas that is around the conductor. One should look carefully at how to protect CICC magnets.

There are other methods of quench protection that have been proposed, but this author has not read about these methods. HTS magnet quench protection is a serious issue.

Poster C3Po1B-09

* This work was supported by the Office of Science, US Department of Energy under contract DE-AC-02-05CH11231

Wednesday 24 July 2019 morning