Quench Protection of an Insulated ReBCO Solenoid by putting Current at the Coil Center

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Abstract: It is well understood that HTS Conductors have a low quench propagation velocities due to high conductor specific heat with increased temperature. An HTS conductor with very little copper has low value of the integral of J^2dt between the magnet operating temperature and 300 K. Adding copper to an HTS conductor reduces the quench velocity within the coil and makes the coil thicker, but it increase the integral of j^2dt between the operating temperature and 300 K. The extra copper makes the quench harder to detect. A method that has been demonstrated to work in some configurations such as thin solenoids is putting a large current pulse into the magnet via a center tap. This method was demonstrated over forty years ago in a large two layer high current density LTS solenoid. This method is more effective if the solenoid is well coupled to a shorted secondary winding.

Introduction

HTS and A-15 conductors have nagging problems for magnet applications:

1. Nb_3Sn and 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 reacted in an O_2 atmosphere. Cu can't be added to the conductor and magnet fabrication is expensive. ReBCO tape are not reacted, so it can have Cu in it and 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 4 K coils.
5. Tape conductors are anisotropic in J_c, B_c, and T_c.
6. HTS conductors are expensive and good cryostats are still needed.

Properties of ReBCO HTS Tapes

Figure 1 shows the quench propagation velocity along a SuperPower HTS tape as a function of the conductor overall current density J, the conductor temperature T and at two values of magnetic induction B [1]. Figure 2 shows the conductor critical current of a Fujikura 4-mm wide ReBCO tape with 20 microns of Cu (~31 percent Cu and Ag) with B perpendicular to the tape as function of T and B [2]. With a 50 µ hastalloy layer, J is 1000 A per square mm at I ~ 300 A.

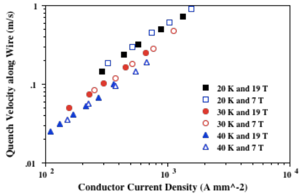

Fig. 1 Propagation Velocity vs Current Density B and T [1]

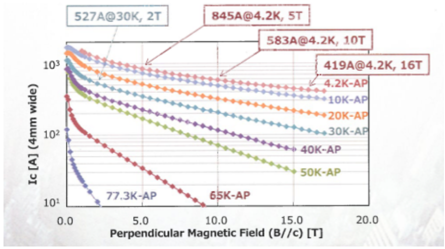

Fig. 2 I_c versus Magnetic Induction B and T for Fujikura ReBCO 4 mm wide Tape [2]

The Basic Quench Protection Problems

Fundamental adiabatic equations that govern quench protection are based on the normal current is carried only in the Cu all of the conductor volume absorbs the of the resistive heat generated in the Cu [3].

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

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

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

Where C is the Cu volume specific heat, ρ is the Cu electrical resistivity, and *f* is the fraction of the Cu in the conductor. The voltage needed to protect a coil with a resistor is as follows;

$$V_0 = \frac{I_0 L_1}{\Gamma F(T)_{HS}} \frac{1}{f} J_0^2$$

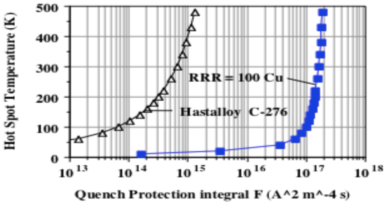

Fig. 3 Cu and Hastalloy 276 for ReBCO Wire Hot spot temperature VS F

The 1977 LBL LTS Coil Experiment

The experiment with a J coil (J = 840 A mm^{-2}) 2-m diameter coil with E = 1.9 MJ compared three quench protection methods that included quench-back alone from the 9.4-mm thick 1100-O aluminum mandrel, quench back induced by a varistor across the coil leads, and quench-back induced by a pulse of current into the coil via a center tap between the two coil layers. The third method is discussed in this paper as a potential means for protecting an HTS coil made from ReBCO tape.

All three methods worked for the LBL coil that is shown in figs. 4 and 5. [4]. The varistor method worked very well, but the high voltages across the coils could persist for some time, which might lead to problems. Quench back alone worked OK, but it couldn't be justified for a coil with a stored energy of 10 MJ. The third method worked better than quench-back alone, because the third method drove the quench-back process faster by turning the coil normal faster. The varistor method would work when the mandrel was thermally insulated from the coil [5]. LBL used quench propagators along the coil. This method failed because the quench zone induced by the longitudinal quench propagators was less than one MPZ.

Fig. 4 Two meter diameter LBL solenoid [4].

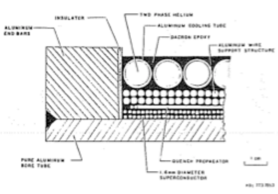

Fig. 5 Two meter solenoid cross-section [4].

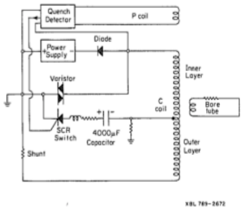

Fig. 6 Pulsed Current Quench Protection Circuit for the two-layer magnet [4].

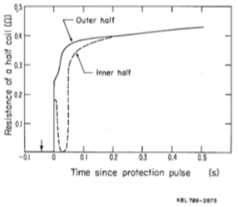

Fig. 7 The inter and outer coil resistances as a function of time for the two-layer magnet shown in Figs 4 and 5 [4].

The magnet shown in Figs 4 and 5 is a two layer coil that is 2-meters in diameter and 0.5 meters in length. It was one of four development coils that led to a large detector magnet for the PEP-4 detector in it at SLAC. The coil was wound with two layers 1.5 mm in diameter (uninsulated) of Nb-Ti with a layer of glass cloth between the layers and vacuum impregnated with epoxy. The Nb-Ti had a Cu to S/C ratio of 1.8. The coil was wound on an RRR = 20, that formed a shorted secondary that would speed up the quench process in the coil. The two layer coil had a self inductance of 1.81 H. The peak current in the magnet was about 1440 A, the a peak magnetic induction at the end of the magnet of about 2 T. At peak peak current the coil stored energy was about 1.9 MJ. The peak current density in the coil was 840 A mm^{-2}.

When the capacitor put the current into the coil. The current rose 1000 A in the outer layer and went down over 500 A in the inner layer in about 1 ms. Most of the outer coil was turned normal within 10 ms. The inner coil became partially normal and then went back to being superconducting. The total discharge energy from the capacitor was ~2 kJ. Both coils were fully normal after 200 ms. The energy in the magnet ended up mostly in the mandrel. It appears that the outer coil was affected little by the mandrel, but the role of the mandrel on the quenching of the inner coil is not clear. Since the center tap quench protection system was not tested on a magnet with a 304 stainless steel mandrel, we don't know the affect of the mandrel to coil heat transfer.

The pulsed center-tap quench protection system was used on the PEP-4 detector solenoid E = 10 MJ and J = 650 A mm^{-2}. This quench protection system became very costly because the capacitor bank had to be kept charged continuously for stored energies of 10 kJ. In retrospect, the varistor quench protection system may have been less expensive. In the PEP-4 magnet, quench back from the mandrel was an important part of the quench protection. At the currents that the PEP solenoid was operated at during experimental operation, it was clear that no active quench protection was needed. By the 1980s detector magnet technology changed.

Will the Center-tap Quench Protection work on ReBCO Solenoids?

The answer to the question above is YES to some degree. This method quench protection will work best in layer-wound ReBCO solenoids where the distance between the current centers of the two layers is small, which means that the energy stored in the capacitor is minimized. For an insulated layer-wound coil with 24 micron of Cu and Ag, 50 microns of hastalloy and 50 microns of insulation is about 0.13 mm compared to the 1.6 mm in the LBL coil. There is a large however in the analysis and that is the energy needed to turn the superconducting layers normal. If one assumes that the HTS coil is at 25 K, the energy needed to turn the coil is at least two orders of magnitude higher. If one wants to change the amount of the coil quenched from two layers to say sixteen layers, the stored energy in the capacitor bank must go up another order of magnitude. If one wants to protect a coil made with double pancakes coil of 12 mm tape, one must also look at the amount of energy that must be stored in the capacitors to quench enough of the coil rapidly to keep the hot-spot temperature below 300 K. A well-coupled shorted secondary circuit would be helpful in shifting current out of the coil.

Using a center tap in a coil to transfer energy from a capacitor bank into a superconducting coil may be a way of protecting ReBCO or BSSCO inserts that produce high fields with either superconducting outer coils are water-cooled copper coils. This method appears to be able to get heat into the center of a coil faster than a conventional heater, because thermal diffusion time constants are longer than the discharge time constants to get energy into a coil. The cost of keeping a capacitor bank charged is not trivial.

References

[1] M. Boturra and C. Senatore, University of Geneva Slides presented for paper WAMHTS3 at EUCAS-12, Lyon France (2015).

[2] Datasheet from Fujikura ReBCO based HTS Superconducting 2G Tape, Telephone 1 (919) 847-6173 in North America, HTS@fujikura.com (2019)

[3] P. H. Eberhard et al, "Quenches in Large Superconducting Magnets," *Proceedings of the 6th International Conference on Magnet Technology* **MT-6,** Bratislava Czechoslovakia, pp 654-661, (1977).

[4] J. D. Taylor et al, "Quench Protection of a 2 MJ Magnet," *IEEE Trans. Mag.* **MAG-15,** No. 1, pp 855-859, (1979).

[5] M. A. Green and X. L. Guo, "Protection of Large Insulated React and Wind HTS Solenoids and Toroidal Coils," IEEE Trans. Appl. Supercond. **29**, No. 5 article 4702507, (2019).

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