Various Quench Protection Methods for HTS Magnets

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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.

1. Introduction
The discovery of HTS superconductivity [1] is the first of three discoveries that caused people the think about the possibilities for a world with little or no losses due to electrical resistance in electrical devices. The discovery of superconductivity by H. Kamerlingh Onnes in 1911 when he demonstrated that the resistivity of mercury could be reduced by at least five orders of magnitude by cooling to a temperature of 3 K in liquid helium at ~25 kPa [2], [3]. At the time, the discovery of superconductivity was heralded as something that would benefit mankind. There were limitations due to the fact that type 1 superconductors existed only at low magnetic fields with limited currents that could be carried. Type 2 superconductivity was certainly discovered before it was demonstrated in niobium tin in at magnetic inductions of 8.8 T in 1961 [4]. The fact that superconductivity could be maintained at high magnetic fields made superconducting magnets a real possibility. There was real excitement within the particle physics community [5]. Conductors such as Nb-Zr and Nb-Ti became of interest because they were strong ductile materials that didn’t require any sort of reaction before the superconductor was created. Magnets were built from these conductors in the 1960s had flux jumps and wire motion that caused magnets made from these materials to quench long before they reached short sample current along the load line [6]. Quenches often resulted in damage to the magnet, because there was little or no copper in the conductor. In 1965 the concept of cryogenic stability was introduced [7]. By the early 1970s, the superconducting community understood intrinsic stability and dynamic stability [8]. As a result, large bubble chamber magnets were built, accelerators with a bending field and focusing field created by superconducting magnets could be considered, and superconducting electrical equipment could be fabricated. Before HTS conductors were discovered all of these things were being done with LTS conductors, including the NMR and MRI magnets.
The discovery of HTS conductor changed the field. It also generated a lot of attention from the press until cold fusion came along. HTS conductors have not performed as well as the press in the 1980s told the public that it would; neither did cold fusion. Plots of \( J_c \) versus temperature and magnetic induction were and still are plotted with \( J_c \) or \( I_c \) on a log scale while \( B \) and \( T \) are plotted on a linear scale. This fact alone made it difficult to compare the two types of conductors. This author tried to come up with a way of characterizing the \( J_c, B \) and \( T \) face of HTS conductor as \(~0.01\%\) lower quench velocity compared to Nb-Ti, which translates to about a factor of \(~2\) lower quench velocity compared to Nb-Ti for a given current density. MgB\(_2\) at 20 K, has a specific heat factor of \(~3\). Second, most Nb-Ti conductors are over fifty percent copper, whereas HTS conductors have less copper or its equivalent within them. The average thermal conductivity in the HTS conductor is much lower than for a typical Nb-Ti conductor. The thermal diffusivity of an HTS coil is typically over three orders of magnitude lower than for a Nb-Ti coil. Niobium tin and magnesium di-boride coils lie between Nb-Ti and HTS coils in terms specific heat and thermal diffusivity. Finally, HTS tape conductors have a lower critical current and engineering critical temperature when the field is perpendicular to the tape face than when it is parallel to the tape face [15]. BSSCO wire and cable conductors show less anisotropy. Anisotropy increases with magnetic induction [16]. These factors have an effect on quench propagation and protection.

2. The Basics of Quench Propagation and Quench Protection

Before going to the basics of quench propagation and protection, the author should define what quench is. This author has experienced a lot of them, since he heard his first quench of an unstable LTS magnet in 1965. LTS magnets quenched for unknown reasons, discharged rapidly, and released a plume of helium gas from cryostat relief valve. In 1965, we began to understand that the amount of copper in the conductor and whether liquid helium was in contact with the copper had a bearing on whether the magnet quenched was close to its short sample current along coil load line at its maximum field region. An insulated HTS magnet is unlikely to be quenched by flux jumps or coil conductor motion. Copper plays a role in dampening flux jumps and the effects of conductor motion. HTS conductors are often used at the edge of its engineering critical induction. HTS conductors often have lower \( n \) values than Nb-Ti. Since the temperatures are higher, the heat transfer coefficients are also higher. A magnet that is resistive in more than one place may be stable. Reliably determining the onset of the magnet resistance in running away is extremely important and it must be done quickly.
There are two factors that must be considered when looking at quenching of HTS magnets. The first is the quench propagation velocity with in the coil. The second is integral of current density squared with time, which determines the maximum hot-spot temperature of the coil, which is usually where the quench started. The basis for quench behavior in LTS magnets is found in an equation developed by Cherry and Gittleman [17]. This is the basis for adiabatic quench propagation and quench protection. Both are discussed in a paper by Eberhard et al in 1977 [18] and by Wilson in 1983 [19]. While quenching of HTS magnets may be more complicated than an adiabatic theory, in the limit of high conductor current densities and high stored energies one should look at LTS quench propagation and protection as a guide on how to protect HTS magnets. Figure 1 and 2 above provide some insight as to what the problems of HTS magnet quench protection are.

2.1. Quench Propagation in HTS Tapes and Wires in Insulated Coils

A more detailed derivation of the quench propagation velocity in the direction of current flow is shown in [20] and [21]. A general expression for quench propagation velocity along the wire that can be applied to both LTS and HTS conductors is as follows;

\[ V_c \approx 0.6 J \left[ \frac{L T_s}{C_s (h_s - h_o)} \right]^{0.5} \]  

(1)

where \( V_c \) is wire quench velocity (m/s) along the wire, \( J \) is the wire current density (A m\(^{-2}\)), \( T_s \) is the superconductor pseudo-critical temperature (K). For an LTS conductor \( T_s = Tc \) and for HTS conductor \( T_s = (Tc+Tcs)/2 \) [15], where \( Tc \) is the conductor critical temperature and \( Tcs \) is the engineering critical temperature. \( L \) is the Lorenz number \( (L = 2.45 \times 10^8 \text{ W} \Omega \text{K}^{-2}) \). \( C_s \) is the volume specific heat of the conductor at a temperature \( T \) (J m\(^{-3}\) K\(^{-1}\)), \( h \) is the volume enthalpy of the conductor at \( T_s \), and \( h_s \) is the volume enthalpy of the conductor at the magnet operating temperature \( T_0 \). From (1), one sees that the quench propagation velocity is independent of the copper to non-copper ratio \( r \), and the conductor thermal conductivity for both LTS and HTS conductors [18], [15]. Figure 1 shows ReBCO quench velocity along the wire versus the conductor \( J, T \), and \( B \).

2.2. Conductor Burn-out Integral of \( J^2 \) dt

There is a general function \( F(T) \) that is a function \( T \). \( F(T) \) is a function of the volume specific heat \( C(T) \) over \( \rho(T) \) the conductor electrical resistivity. For each material in a conductor there is an \( F \) that applies between the conductor operating temperature \( T_0 \) and some hot spot temperature \( T_{hs} \) that is a function of the integral of \( J^2 \) dt during the decay of the current density from \( J_0 \) to \( J = 0 \). This \( F \) function is as follows;

\[ F(T_{hs}) = \int_0^{T_{hs}} \frac{C(T)}{\rho(T)} \, dT = \int_0^{\infty} J(t)^2 \, dt, \]  

(2)

Figure 2 shows the calculated value for Hastalloy C-276 and RRR = 100 copper as a function of temperature. At 50 K there is a four orders of magnitude difference between the two values of \( F \). At 300 K the difference is \( \approx 500 \). To first order, \( F \) of the conductor is the \( F \) of copper times the copper fraction \( f \). If the superconductor has any copper in it most of the current will be carried by the copper (or some other low resistivity metal such as silver) after the superconductor turns normal. Thus, the heat is generated mostly in the low resistivity normal metal whereas the heat heats up both the low resistivity normal metal and the superconductor and other metal in the conductor. Thus, we can define an \( F^* \) for a quench of most superconductors the equation for the conductor \( F^* \) is as follows;

\[ F^*(T_{hs}) = \frac{1}{f} \int F(T_{hs}) \rho Cu \approx \frac{1}{f} \int_0^{\infty} J(t)^2 \, dt, \]  

(3)

where \( f \) is the fraction of copper in the conductor. In a ReBCO tape, one assumes that the tape is copper and Hastalloy. The superconductor in the normal state is assumed to have properties like
Hastalloy and the silver is like copper. Because copper has a much larger value of $F$ than Hastalloy (see Fig. 2), and the resistivity of copper is at least two orders of magnitude lower than Hastalloy thus (3) is valid for conductors with $f < 0.02$. A ReBCO conductor with no copper has $f = 0.04$. BSSCO tape silver behaves like copper, the same $F^*$ equation may hold for $f$ down to ~0.05.

![Figure 1 Measured quench propagation velocities for SuperPower tape that is ~44 percent Cu and Ag. Most of the rest is Hastalloy C-276 [15]](image)

![Figure 2. The Quench propagation integral $F$ for RRR = 100 copper and Hastalloy C-276](image)

Discharging a superconducting coil across an ordinary resistor produces an exponential current decay with a time constant $\tau$, where $\tau = L_1/R_1$. An exponential current decay can be integrated from time zero to infinity to yield an $F^*(T_{HS})$ at the end of the discharge, which is as follows;

$$F(T_{HS})^* = \frac{L_1}{F(T_{HS})} \frac{1}{f} J(0)^2,$$

where $f = 2$ for a constant resistance resistor and $f = 3$ for a perfect constant voltage resistor [18]. $R_1(0)$ is the resistance at the current when $t = 0$. A varistor is not a perfect constant voltage resistor, but it can reduce the $F^*(T_{HS})$ by almost a third. There is a discharge minimum starting voltage for safe quenching even when there is no coil quench propagation. This starting voltage is given as follows;

$$V_0 = \frac{I_0 L_1}{E_F J_0} \frac{1}{f} J_0^2,$$

where $V_0$ is the discharge voltage at $t = 0$ when the switch is open; $J_0$ is the conductor current density at $t = 0$; $I_0$ is the coil current at $t = 0$; $L_1$ is magnet self-inductance; and $F(T_{HS})^*$ is defined by (3). The discharge voltage in (4b) assumes the quench is detected at $t = 0$. If the quench is not detected quickly, the value of $F^*$ must go up, so the discharge voltage also goes up.

By manipulating the equations above, one can up with the expression that shows the relationship of the coil stored energy $E_0$ at a current of $I_0$ and a conductor current density of $J_0$ to $F(T_{HS})^*$ and the quench discharge voltage $V_0$ at the start of the discharge. This expression is as follows [21];

$$E_0 J_0^2 = f F^*(T_{HS}) V_0 I_0.$$  

Conventional wisdom says that from (5), if wants to quench protect a magnet or magnet module with a stored energy $E_0$, one must increase the magnet current $I_0$, and reduce the coil current density $J_0$ by increasing $f$, while discharging the coil at the highest voltage $V_0$ that is reliably safe. HTS conductors don’t respond very well to conventional wisdom, so other ways of protecting high current density coil must be devised. The remainder of the report discusses some methods that have been proposed.
3. Quench Protection Methods for HTS Magnets

This section talks about quench protection methods that could be used for HTS magnets. The thoughts on this are the author’s. The ideas presented in this section are presented from the author’s experience with magnets made from LTS conductors. Many ideas presented in this section have been successfully tried on HTS magnets, but in virtually all cases the magnet stored energy is low. When magnet stored energies are increased from a few kJ to even a few MJ, many methods don’t work very well for various reasons. The things that the reader should remember are: 1) Quenches don’t propagate rapidly in HTS conductors. This can be true for conductors at temperatures in the range from 5 K to 10 K. 2) The isotropic behavior in thin film or tape conductors means that the engineering critical temperature and critical induction varies with the field orientation. So, quench propagation speeds and energy to cause the conductor to quench are a function of magnetic induction and field orientation. 3) The specific heat of the conductor varies as temperature to the third power. The higher the magnet temperature the more energy is takes to drive the conductor normal.

When designing a quench protection system for HTS magnets, it is best to ignore the energy that goes into the coil from the quench. One must remove the stored magnetic energy from the coil so that $F(\text{Ths})$ never reaches a value that is above $\text{Ths}$ is above 300 K. Conventional rules still apply; 1) the magnet should be sub-divided to reduce voltages, 2) the magnet current should be as high as one can make it, 3) one must reduce the conductor current density by adding low resistivity normal medal to the conductor, and 4) the quench protection voltages should be set has high as one can and still be reliably safe from breakdown.

3.1. Methods of Quench Protection that work well in Nb-Ti Magnets

3.1.1. Adding a low resistivity normal metal to increase to increase $f$ and reduce $J_0$. This would be the first thing one would do to make it possible to safely quench any HTS magnet [22]. The $I_0$ chosen is dependent on a number of factors. The biggest factor is the type of refrigeration used to cool the magnet. If coolers are used, $I_0$ will be low. Sub-division of the magnet may be another factor that governs $I_0$. Adding any low resistivity stabilizer increases the length of the minimum quench propagation zone that has several positive effects [23] even in HTS magnets. With HTS magnets there are a number of problems. One can’t add copper to a conductor in an HTS magnet that is wound and reacted. If silver is used in place of copper, this is an option can be considered. For ReBCO magnet conductor, one should consider co-extruding the ReBCO conductor in high RRR aluminium, but the strain seen my the ReBCO must be low. Having a low resistivity strip of material wound with the ReBCO is a possibility, but the insulation is not fully covering the ReBCO and the strip [24]

3.1.2. Using a cold Resistor in series with a cold Diode to heat the magnet coil for a faster Quench when a Resistor is put across the Magnet Leads. This is a quench protection method that has been used niobium tin magnets and the cyclotron Gas Stopper magnet fabricated at Michigan State University [25]. This method dissipates most of the magnet energy inside the cold mass. The heat from the resistor quenches the coil through conduction. This can be very useful large diameter solenoids if the resistor covers the outer and or the inner surfaces of the solenoid coil. Whether or not this method is useful in an HTS magnet depends on its operating temperature and the thermal diffusivity of the coil package. For the most part this method for isn’t useful for HTT magnets but it may be useful magnesium di-boride magnets.

3.1.3. Quench-back from a conductive Tube next to the Coil. Quench-back [26], [27] has been used for solenoids and toroidal coils for LTS detector magnets. This method can be completely passive, or it can be combined with active quench protection methods, such as a resistor across the coil. This method doesn’t work for HTS magnets because of high coil specific heat.
3.1.4. Quench Protection by discharging a Capacitor into the Center-tap of a thin Solenoid. This method has been used in 2 MJ large high current density thin LTS coils [12], [28]. Combining this method with quench-back from a conductive bore tube improves the quench process. This method rapidly changes the current in the two coil layers where the center-tap is located. The energy stored in the capacitor ends up between the two coil layers. Conductor AC losses combined with currents at exceed the conductor critical current cause a portion of the coil to go normal. This method works better when it is combined with the method stated in 3.1.3. This method might work in some HTS coil configurations if combined with other quench protection methods. A reliable capacitor bank is required for this method to be used.

3.1.5. The CLIQ Method of Quench Protection. Coupling loss induced quench (CLIQ) is a method of quench protection that works better than quench heaters [29]. In LTS magnets this method can be used in dipoles and quadrupoles that are made from niobium tin and Nb-Ti cables. Since the quench energies of HTS magnet are much higher, this method is unlikely to be useful for quench protection. This author would not rule out its use for magnet with cable conductors using magnesium di-boride conductors. It is worth a try, but the voltages will be higher.

3.1.6. Quench protection using a well-coupled low-resistivity shorted-secondary and a constant-voltage Resistor across the Coil Leads. This method worked extremely well in a 2 MJ two-meter diameter LTS coil tested at LBL in 1977 [12], [28]. This method involves putting in a constant-voltage resistor across the leads of the coil, which caused ninety-seven percent of the coil current to rapidly flow into RRR = 20 aluminum bore tube inductively. This author believes that this method will work for an HTS magnet if the coils are well-coupled to a secondary [30]. This method can be combined with methods such as 3.1.1 in a number of magnet configurations, even if the secondary circuits are not well coupled to the coil.

3.2 Other Methods of HTS Magnet Quench Protection found in the Literature

3.2.1 Quench Protection by having no insulation between turns and layers. The notion of quench protecting a magnet by having uninsulated turns [31], [32] strikes this author as being non-sense, but there may some advantages to this idea. Shorted turns and layers greatly increase the charging time for a magnet, but because HTS conductors often have flaws in them, the current can be shunted to an adjacent turns or layers at or near the design current [33]. This author would argue that this method prevents the magnet from quenching due to conductor flaws, but the magnet will eventually quench. The other downside to this approach is that a conductor dominated magnet will have field errors due to the currents to shifting turns and layers. This may not be important in an iron dominated magnet where the field structure is determined by the iron. Early in this author’s career, magnets were built without insulation in hopes that the magnet would come close to its critical current along the load line. Early on at Berkeley, we learned that shorted turn magnets with little or no copper do quench, and often the quench ended up damaging the coil. When copper was added to the conductor, so that f was ~0.75, the coil went to short sample, if there was a copper-oxide insulation on the wire. This author may be wrong about this method of quench protection. This author needs more proof to be convinced. The experiments that have been done on magnets with low stored energy and low current densities. This author worries about what would happen when the stored energy and current density are high.

3.2.2. Quench Protection by using Capacitors and Switches to remove Coil Current. This method has been shown to work at low stored energies and low conductor current densities [34]. The experiment used capacitors with capacitances in the range of 1 F. If a capacitor of this size can be discharged rapidly, it would be a good capacitor to use for quench protection method 3.3.4. This author doesn’t see that this method is scalable to large magnets with high stored energies.
3.2.3 Cable in Conduit HTS Conductor Quench Protection [35]. This author hasn’t really looked at quench protecting cable in conduit conductors (CICC). If a conduit can be put around ReBCO cables with extra copper strands, one would end up with a conductor that carries large currents and the current density of the material that is in the conduit would be low. It might be possible to put part of the stabilizer on the inner bore of the conduit as well. Since the quench propagation is driven by heating of the conduit fluid, the quench propagation velocities may be much higher than in the conductor itself. The current densities must be low because of the long time-constants needed to heat the conductor from the fluid by thermal diffusion. This is an area that deserves serious study.

4. Concluding Comments
Quench protection of HTS magnet is a real problem when the stored energies and conductor current densities are high. At high current densities one must get the current out of the magnet very rapidly. The time constant for getting the current out of the conductor is shorter than the time constant to heat the coil from the outside. If one can shift the current from the coil to a shorted secondary rapidly and if one chooses the right current density initially in the magnet conductor, the magnet can be protected by an active quench protection system. One must be able to detect a quench rapidly and reliably. The higher the current density in the conductor, the rapid the quench detection must be.

The areas that show some promise are: 1) inserting ReBCO into a high RRR stabilizer, 2) shunting magnet current into an inductively-coupled magnet component using a constant voltage resistor that reduces the need for stabilizer in HTS conductor for a given hot spot temperature, 3) coil subdivision in a sensible way is needed, and 4) the quenching of CICC magnet should be looked at. These steps along with increasing the coil current \( I_0 \) and the discharge voltage \( V_0 \) across the coil can improve the prospects for protecting HTS magnet with high stored magnetic energies.

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