Protection of HTS Coils in the Limit of Zero Quench Propagation Velocity

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***Abstract*—The observed low quench propagation velocity in HTS superconductors is a problem for the internal protection of magnet coils, which depends on the propagation velocity for the spread of the normal zone. In principle, a distribution of protection heaters can be used to give a large effective propagation velocity, but such a system raises the question of the amount of power and voltage required by the heaters to protect a coil. Here, an analysis is made for the ideal limiting case of zero propagation velocity. In this case, the heated zone adjacent to the heaters is a well defined normal volume. The analysis addresses two issues: determination of the normal volume required for the protection of the coil, and the power and voltage requirements of the heaters. The analysis is applied to two types of HTS coils, including low field coils operating at high temperature of the type that may be used for gyrotron applications, and high field insert coils operating at low temperature. For the example coils studied, the heater voltages are found to be moderate and the analysis indicates that protection by densely distributed heaters is a practical means of protection of HTS coils.**

***Index Terms*—Gyrotrons, high temperature superconductors, quench protection, superconducting magnets.**

I. Introduction

HIGH Temperature Superconductors (HTS) are being developed for a variety of applications including power transmission and magnet coils. HTS conductors used in magnet coils offer the capability of operation at significantly higher temperatures than possible with Low Temperature Superconductors (LTS), while at low temperatures offer the capability of operation at much higher fields than available with LTS conductors. Because of the high heat capacity of the conductor at high operating temperatures, or the high critical properties at low operating temperatures, the velocity of quench propagation is observed to be very low in comparison with LTS conductors [1]. The low quench propagation velocity gives rise to a variety of difficulties and concerns for the quench protection of HTS coils. There is a concern for the lack of propagation of local normal zones, and the possible effects of resulting high temperatures [2]. The detection of a quench when the normal zone and associated voltage may remain small is an issue for quench protection [3]. The focus here is on the protection of an HTS coil after the detection of a quench condition, assuming that the quench can be detected early in the evolution of the temperature of the hot spot normal zone. Protection heaters are often used as part of the protection system for LTS coils, and serve the purpose of effectively increasing the quench propagation velocity in coils or sets of coils, even providing for an effective propagation velocity between thermally isolated coils. Here the possibility of protection of HTS coils with an extended distribution of protection heaters is examined as a way to compensate for the low propagation velocity. The use of a greatly extended distribution of protection heaters raises issues of complexity of design and fabrication. More fundamentally, it is possible to imagine that with a sufficiently large number of heaters, the protection of an HTS coil is assured. What is not assured, and what has not previously been determined, is whether the power and voltage requirements of a distribution of heaters that is sufficient to affect the protection of an HTS coil, are low enough to be compatible with practical quench protection systems.

The general analysis for quench protection with distributed heaters in the limit of zero propagation velocity is first described. The use of the magnet itself as the power source for the heaters is discussed. The analysis is applied to example coils including magnets of the type that may be used for gyrotrons, and insert coils for very high field solenoids.

II. Concepts and Analysis

An analysis is made of the protection of HTS coils in which the low quench propagation velocity is taken to the idealized limit of zero propagation velocity. The protection system is active and internal, relying on active quench detection and dissipation of the magnet stored energy internal to the windings. The natural propagation velocity of LTS conductors is replaced by the action of a distribution of heaters. The spread in the initial hot spot region, essential for internal protection, is accomplished by the normal zones that are induced adjacent to the heaters. The analysis is described as applied to a tape wound solenoid magnet of pancake construction.

The stacked pancakes of the coil construction are typically separated by thin insulators that cover the surface of the pancakes. The heaters for this analysis are assumed to be embedded in the insulators, occupying the same space between the pancakes, and covering some fraction of the surface area of the pancakes. The heated zone associated with the heater is assumed to lie directly adjacent to the heater, and to extend through the thickness of the pancake. In this way, the zero propagation velocity is taken strongly to mean zero thermal conductivity along the direction of the conductor, and for that matter transverse to

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the conductor in the plane of the pancakes. The high thermal conductivity of the conductor stabilizer, copper or silver, is recognized to give a uniform temperature across the width of the tape, equal to the thickness of the pancake. The result is the concept of a volume of coil windings of uniform temperature adjacent to a heater.

The internal protection of a superconducting coil, in which the stored energy is deposited within the windings, requires that a sufficiently large volume of the coil is normal so as to limit the dissipated energy density and associated temperature rise. In the present scheme, the normal volume is only that volume which is driven normal by the heaters. For a coil with initial operating temperature T_0, the selection of a final temperature T_2 of the normal regions determines the fraction of the coil windings that must be driven normal by

$$\delta f_c V = \frac{E}{[H(T_2) - H(T_0)]} \quad (1)$$

where H is the enthalpy at the temperature, E is the magnet stored energy, δ is the mass density of the windings, and f_c is the fraction of the total coil volume V that must be driven normal by the heaters.

In order to be effective in protecting the coil and limiting the temperature of the hot spot normal zone, the heaters must operate quickly to drive the windings normal and initiate the discharge of the coil. In order to quench the coil, the temperature is increased from the operating temperature T_0 to a temperature T_1 substantially above the current sharing temperature if not to the critical temperature. This temperature rise is assumed to occur in the coil volume $f_c V$ determined in (1) in a time interval Δt. The required power is given by

$$P_0 = \frac{[H(T_1) - H(T_0)]}{\frac{\tau}{2}[1 - e^{-2\Delta t/\tau}]} \delta f_c V \quad (2)$$

where the power source is assumed to have an exponential time constant τ, and P_0 is the value of the initial heater power. In order to quench the coil, the temperature T_1 should be substantially above the current sharing temperature if not to the critical temperature.

A configuration of heaters to provide the required power may be determined. It is assumed that there are N heaters. From (1) the volume of the heated zone and from (2) the power associated with one heater is then known. The normal volume associated with a heater is product of the projected heater area and the thickness of the pancake, or equivalently the tape width. Given the normal volume and the tape width, the heater area is known. The power per heater and the area of the heater give the heat flux. The heater configuration is a thin flat strip, and the heat flux is given by

$$F_h = \frac{I_h^2 \rho_h}{w_h^2 t_h} \quad (3)$$

where ρ_h, w_h, and t_h are the resistivity, width and thickness of the heater material, and I_h is the heater current. As the heat flux is known, this expression gives a constraint on the parameters of the heater. For the pancake wound coil, it is natural to select a thickness for the heater, in recognition of the insulation thickness and separation between the pancakes. It will be assumed

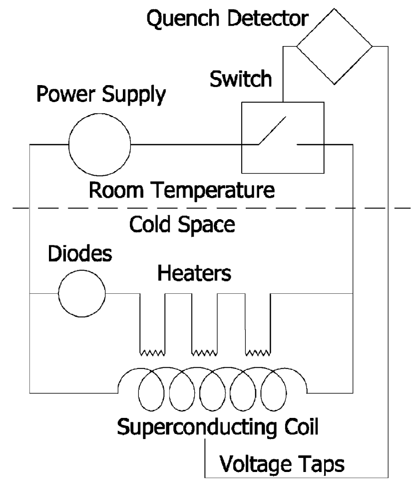

Fig. 1. Protection circuit showing use of the magnet stored energy to power the protection heater network when the contactor switch is opened by the quench detector.

that the current in the heater is known, as will be discussed below. Expression (3) then gives the heater width. The heater area was determined above from the required normal volume and the tape width. The heater length is therefore determined, and the heater parameters are then fully characterized.

III. Heater Power Source

The protection heaters require power for operation. One way to provide the power is to use the magnet stored energy as the source. This type of system has been used previously and can be accomplished even for magnets operating in persistent mode by using a second persistent switch in parallel with the heater network [4]. For a magnet that will operate in powered mode only, the circuit of Fig. 1 can be used. The quench detector opens the contactor switch in response to a quench condition. The magnet transport current then flows in the diode and heater circuit.

IV. Examples

Example calculations of HTS coils are made using the above analysis for the type of low field coil that may be used in gyrotron applications, operating at high temperature, and for high field insert coils as part of very high field solenoids, operating at low temperature. The heater design for gyrotron magnets is given in Tables I and II. Parameters for the size and field of a prototype HTS gyrotron magnet have been given previously, and these quantities are reflected in the parameters in Table I for Coil A [5]. A description of the performance of HTS conductor in terms of critical current as a function of field and temperature is not within the scope of the present work, and no attempt was made to design the coils in this study from first principles. In the case of the gyrotron magnets, a current density of 100 A/mm^2 was first chosen on the basis that the gyrotron application will eventually require coils of reasonably compact size. However, examination of the present performance of YBCO coated conductors supports the possibility presently or in the near future of such current densities even allowing for field perpendicular the broad face of the tape, in coils of this field value operating at a temperature in the neighborhood of 55–60 K [6]. The current

TABLE I
EXAMPLES OF HEATER PROTECTION FOR LOW FIELD HTS COILS OPERATED AT HIGH TEMPERATURE

		Coil A	Coil B
Inner radius	a_1(mm)	60	120
Outer radius	a_2(mm)	95	154
Winding length	2b(mm)	216	432
Average current density	Jave(A/mm^2)	100	100
Conductor current density	Jcond(A/mm^2)	131	131
Number disks	N	48	96
Operating current	I_o(A)	57	57
Central field	B_o(T)	3.6	3.6
Coil volume	Vol(cm^3)	3.7x10^3	12.2x10^3
Stored energy	E(kJ)	20.1	129.0
Heater area fraction	f_c	0.038	0.072
Power/heater	P_h(w)	49	158
Heat flux	F_h(w/cm^2)	7.5	7.5
Heater thickness	t_h(mm)	0.05	0.05
Heater width	w_h(mm)	24	24
Heater length	l_h(mm)	27	87
Total heater resistance	R(Ω)	0.74	4.8
Total heater voltage	V(v)	42	268
Total heater power	P(kw)	2.34	15.1

TABLE II
THERMAL PARAMETERS FOR HEATER PROTECTION OF LOW FIELD HTS COILS OPERATED AT HIGH TEMPERATURE

Operating temperature	T_0(K)	55
Intermediate temperature	T_1(K)	70
Final temperature	T_2(K)	150
Intermediate enthalpy	ΔH_1(J/g)	2.1
Final enthalpy	ΔH_2(J/g)	23.3
Heater time	Δt(s)	1
Decay time constant	τ(s)	4

density leads to the coil size, volume and stored energy. The operating current and the number of pancakes in the coil follow from the tape width of nominally 4 mm. Coil B is arbitrarily chosen to be twice the size as Coil A in order to observe the influence of the increased stored energy on the coil protection.

Table II gives to coil operating temperature T_0, the temperature T_1 after heater operation for a time interval of Δt, and the final temperature of the normal zones T_2. The operating temperature of 55 K is interpreted to give a margin for stability, with the current sharing temperature assumed to be 60 K. The intermediate temperature of 70 K is interpreted to normalize the majority of the windings far into current sharing, and therefore to have quenched the coil. The final temperature of 150 K is a conservative value to avoid issues of thermal stress. The assumed enthalpy changes for the windings at these temperatures are shown. As seen in Table I the required heated fraction fc of the coil windings, at 4% to 7%, is relatively small. The initial power per heater and the associated heat flux are computed as indicated above. The heat flux is judged to be moderate and without issues of thermal induced stress in the proximity of the heater. An allowance is made through the time constant τ that the magnet current, and therefore the current to power the heaters, will decrease during the initial time increment Δt. The total voltage on the heater circuit as shown in the table is relatively low, even for the larger magnet, so as not to require unusual provisions for heater electrical insulation.

TABLE III
EXAMPLES OF HEATER PROTECTION FOR HIGH FIELD HTS INSERT COILS OPERATED AT LOW TEMPERATURE

		Coil C	Coil D
Inner radius	a_1(mm)	30	60
Outer radius	a_2(mm)	83	136
Winding length	2b(mm)	243	300
Average current density	Jave(A/mm^2)	200	150
Conductor current density	Jcond(A/mm^2)	244	183
Number disks	N	54	65
Operating current	I_o(A)	158	158
Central field	B_o(T)	30	30
Coil volume	Vol(cm^3)	4.6x10^3	14.0x10^3
Stored energy	E(MJ)	0.34	1.4
Heater area fraction	f_c	0.44	0.58
Power/heater	P_h(w)	346	1169
Heat flux	F_h(w/cm^2)	4.2	4.3
Heater thickness	t_h(mm)	0.05	0.05
Heater width	w_h(mm)	91	90
Heater length	l_h(mm)	90	302
Total heater resistance	R(Ω)	0.75	3.1
Total heater voltage	V(v)	119	482
Total heater power	P(kw)	18.7	76.0

TABLE IV
THERMAL PARAMETERS FOR PROTECTION OF HIGH FIELD HTS INSERT COILS OPERATED AT LOW TEMPERATURE

Operating temperature	T_0(K)	4.2
Intermediate temperature	T_1(K)	30
Final temperature	T_2(K)	150
Intermediate enthalpy	ΔH_1(J/g)	0.26
Final enthalpy	ΔH_2(J/g)	25.3
Heater time	Δt(s)	0.2
Decay time constant	τ(s)	3

The analysis for high field insert coils is given in Tables III and IV. Recent progress in YBCO coated conductors and coil technology makes 30 T a practical objective and relevant choice for an example. Coil C is intended to be the inner coil of a general high field research solenoid. Coil D is selected to examine the effect of increased coil size. The field increment produced by the coils shown in Table III is 12 T. Recent data of commercial YBCO coated conductors at low temperature indicate very high critical currents, and the performance of these conductors has been demonstrated in a small coil at high field [7]. These results are the basis for the selection of the current density of Coil C. The current density of Coil D is reduced on the basis that the large coil may need additional structural reinforcement.

The temperature and enthalpy parameters for the insert coils are given in Table IV. For coils designed to operate at 4 K, the intermediate temperature of 30 K is interpreted to normalize the windings far into current sharing. The final temperature of 150 K is typical and low for the allowed hot spot temperature of high current density superconducting windings. The magnetic stored energy of an insert coil consists of the self stored energy and the energy associated with the mutual inductance coupling to the outer coils. During a quench, if an inner coil is to avoid inductive energy transfer from the outer coils, the decay time constant of the inner coil must be at least as fast as the outer coils. In that case, the inner coil will need to absorb at least the

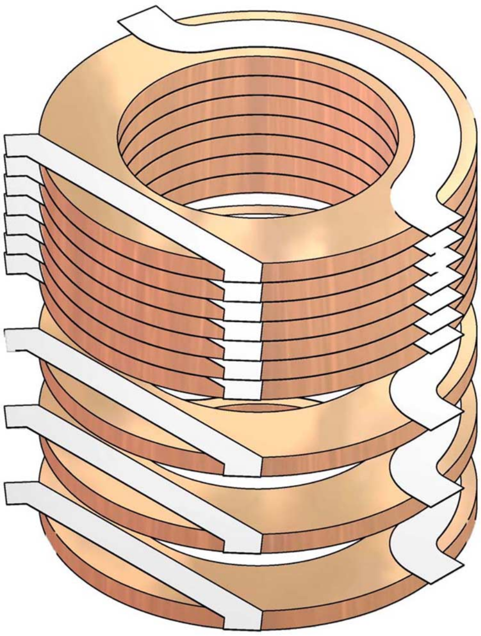

Fig. 2. Exploded view of pancake coil windings, showing concept of distributed heaters as heater strips on each pancake, with different heater configurations and degree of coverage of the pancake area.

self plus mutual inductance energy, and this is the energy given in Table III. As a result of the resulting large energy density of the inner coil, the fraction of the windings f_c that must be made normal by the heaters is large as seen in Table III. The heaters are assumed to operate rapidly with a heater time increment Δt of 0.2 s, in order to protect the inner coil against a rapid quench of the LTS outer coils. Because of the reduced enthalpy at low temperatures, the required heater voltages and power are still limited to values that are practical for coil protection without extraordinary measures.

Two example forms of heater are shown in Fig. 2. The straight strip is simple in construction and easily provides a low fraction of heater area on the windings. The curved sections can more readily provide a larger fraction of heater area. Heater segments can be used in series or parallel depending on the length and width requirements of the heater.

V. Conclusions

For the example coils, employing HTS conductors operating at both relatively high temperature and low temperature, it is seen possible to protect the coils even in the limit of zero propagation velocity by employing a densely distributed set of protection heaters. In particular, the power requirements of the heater set and the associated voltage when the heaters are powered by the magnet transport current are practical values for the design of coils.

References

[1] W.-S. Kim, F. Trillaud, I. C. Ang, S. Hahn, and Y. Iwasa, "Normal zone propagation in YBCO winding pack models," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 2478–2481, 2007.

[2] A. L. Mbaruku, U. P. Trociewitz, X. Wang, and J. Schwartz, "Relationships between conductor damage, quenching and electromechanical behavior in YBCO coated conductors," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 3044–3049, 2007.

[3] F. Trillard, I. C. Ang, W.-S. Kim, H. G. Lee, Y. Iwasa, and J. P. Voccio, "Protection and quench detection of YBCO coils results with small test coil assemblies," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 2450–2453, 2007.

[4] W. D. Markiewicz, I. R. Dixon, C. A. Swenson, W. S. Marshall, T. A. Painter, S. T. Bole, T. Cosmus, M. Parizh, M. King, and G. Ciancetta, "900 MHz wide bore NMR spectrometer magnet at NHMFL," *IEEE Trans. Appl. Supercond.*, vol. 10, pp. 728–731, 2000.

[5] R. W. McGhee, E. E. Burkhardt, A. Berryhill, and D. M. Coffey, "Design and test results of a BSCCO-2223 magnet for gyrotron application," *IEEE Trans. Appl. Supercond.*, vol. 15, pp. 1189–1191, 2005.

[6] X. Song, Z. Chen, S. Kim, D. M. Feldman, D. C. Larbalestier, J. Reeves, Y. Xie, and V. Selvamanickam, "Evidence for strong flux pinning by small, dense nanoprecipates in a Sm-doped YBa2Cu3O7- δ coated conductor," *Appl. Phys Letters*, vol. 88, p. 2125008, 2006.

[7] D. Hazelton *et al.,* in *Proceedings MT-20*.