IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

ELECTRICAL PROTECTION OF SUPERCONDUCTING MAGNET SYSTEMS

D. F. Sutter and R. H. Flora
Fermi National Accelerator Laboratory*
Batavia, Illinois

Summary

The problem of dissipating the energy stored in the field of a superconducting magnet when a quench occurs has received considerable study. However, when the magnet becomes a system 4 miles in length whose normal operation is an ac mode, some re-examination of standard techniques for dissipating energy outside the magnets is in order. Data accumulated in the Fermilab Energy Doubler magnet development program shows that heating associated with the temporal and spatial development of quenches is highly localized and can result in temperatures damaging to the superconducting wire. This paper reviews the design and operation of several energy dumping schemes, compatible with the operation of ac superconducting magnets, wherein more than 70% of the stored energy can be dissipated outside the magnet. Instrumentation to detect quenches early in their development and circuits for dumping the field energy are described, and representative operating performance data for the dump circuits and data showing temporal development of quenches are presented.

Scope

The Fermilab Energy Doubler, a slow cycling superconducting accelerator, will require some 744 dipole and 240 quadrupole magnets distributed around a 4-mile circumference ring. The total stored energy is predicted to be about 415 Megajoules, ∿ ½ Megajoule per dipole and one tenth that for each quadrupole.[1] If, as tentatively planned, the magnet system is powered by supplies similar to those used in the present Main Ring, the smallest subset of magnets that can be controlled from one supply will consist of 8 quadrupoles and 32 dipoles, corresponding to a peak stored energy of ∿ 18 MJ. Since spatial and economic constraints require that these magnets have small cross section and limited liquid helium inventories, they cannot be expected to internally dissipate all of the energy stored in their magnetic fields without risking coil damage.

There are two principle aspects to the problem of protecting a superconducting magnet when a quench occurs: dissipating the field energy so as to avoid destructive internal temperature rises, and keeping magnet terminal voltages within safe limits. Both topics have been studied extensively for large inductance dc magnets, principally solenoids, but not for small cross section, high aspect ratio ac magnets of the type to be used in the Energy Doubler.[2] Analysis of the problem of internal temperature rise involves determining the velocities of propagation of the developing normal zone in the longitudinal, azimuthal and radial directions and noting how its growth affects temperature.[3-7] Control of terminal voltages is dependent on the energy dumping circuits.[8-11] A comprehensive survey of the many forms these circuits can assume will be found in the article by Watrous.[9] Some typical examples are shown in Figure 1. As a general principal, efficiency of fault protection depends strongly on early detection of the quench.

This study is primarily concerned with extending previous work to include the special problems associated with protecting slow cycling magnets having an inductance < 200 mH and peak operating currents > 1000A and

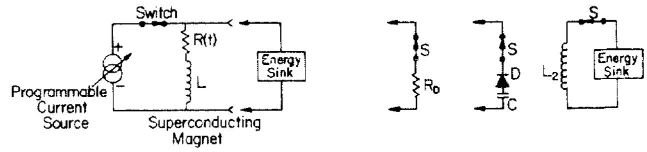

Fig. 1. Some representative schemes for dissipating energy external to a superconducting magnet during a quench.

with application of this knowledge to protecting magnets in an array to be used for a superconducting accelerator. The following assumptions have been made: All magnets in the accelerator ring are powered in series during regular operation by power supplies that are good approximations to ideal current sources. These supplies produce a time varying current output that precisely tracks an input programming waveform and have enough reserve voltage capability to drive significant amounts of current through the one magnet that has gone normal in a large array of superconducting magnets. Terminal voltages for a single magnet or throughout an array must be controlled so as to limit voltage to ground to ≤ 2500 Volts. Economic considerations require that protection schemes not contribute significantly to the refrigeration heat load. This affects the number and type of penetrations from 300K to 4.2K allowed for energy dumping circuitry; however, a low-level contribution to the heat load during ac operation is acceptable. Since in an operating accelerator a quench represents anormal operation, which in theory never happens, the dissipation of total field energy within the helium bath is acceptable. This accepts the reality that the magnets always dissipate some fraction of the energy internally and says that the occasional vaporization of the 4.2K liquid charge is probably a less severe penalty than the steady heat load imposed by many penetrations to room ambient.

None of the assumptions outlined seriously alter application of the energy dumping schemes presented in the references to a single ac excited magnet. Considering an array, however, only two alternatives seem possible: either find some way to isolate the faulting magnet by a clever switching scheme, or else remove the energy of the entire array, in parallel, at each magnet simultaneously. Isolating a quenching magnet and safely dissipating its field energy, while at the same time maintaining the rest of the array of magnets in a superconducting state, appears to be an unattractively complex problem. Consequently, it has been assumed that the field energy must be removed in parallel, which means that the entire array is to be triggered into the energy dumping mode as soon as a quench is detected. The unattractiveness of penetrations to ambient raises a question fundamental to both strategies: do electronic switches exist that can handle surges up to 100 kA and 20 volts, as required for transformer secondaries, or up to 4000A at 1000 volts, as for primary circuits, and that can still operate reliably in a 4.2K to 20K ambient. Our immediate concern then seems to be to acquire an understanding of some single magnet dumping schemes, and to try to judge their adaptability, singly or in combination, for implementing one of the strategies described for large arrays.

*Operated by Universities Research Association, Inc., under contract with the U. S. Energy Research and Development Administration.

Model Studies

We elected to examine the performance of three circuits: the resistive dump of Figure 1a, the transformer coupled circuit of Figure 1d, and a transformer coupled circuit similar to Figure 1d, but without a switch. The resistive dump, using an SCR as a switch, is the most likely candidate for the energy sinks, E.S., in the subdivided array shown in Figure 2. This is the "protection by subdivision" scheme of Smith.[7] Transformer coupling is of particular interest, in spite of anticipated difficulties in achieving high efficiency, because it fails safe - even if a magnet lead opens up, is the only protection method that dissipates energy when a turn-to-turn short occurs, gives a parallel energy dissipation at low voltages isolated from the primary, is readily adaptable to electronic switching and could be mounted on a heat shield operating at some temperature greater than 4.2K.

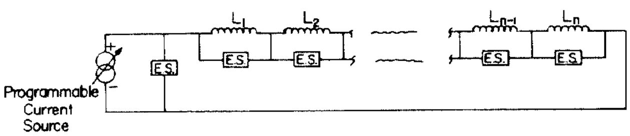

Fig. 2. Energy dumping with an array of superconducting magnets. All energy sinks (E.S.) are potentially allowable.

Mathematical Models

Detailed modeling of the three test circuits, and others, can be found in the cited references. For simplicity we have assumed that internal resistance, as seen across the magnet terminals, develops linearly with time, $R(t) = \gamma t$. In the absence of detailed computations of normal zone propagation velocities for the particular magnet geometry under test, this is not a bad model. We are interested in two fault modes for each magnet, one triggered externally when there is no quench (the "snap-off" case) and one triggered by a true quench that trips the safety circuit. The snap-off case is germane to a system that triggers all magnets, quenching and non-quenching, into the dump mode as soon as a quench is detected.

The circuit equation that applies to the resistive dump, Figure 1a, is:

$$L \frac{dI}{dt} + (R_D + \gamma t)I = 0. \qquad (1.$$

If the γt term remains zero during a snap-off, then all field energy would be dissipated in R_D. This is physically unrealistic; the rapidly collapsing field will eventually cause a large section of the magnet to go normal via eddy current heating. If the normal zone resistance, $R(t)$, could be represented by some mean value R_m, averaged over an interval long compared to the energy dissipation time, then the dump efficiency ξ, defined as the energy dissipated outside the magnet divided by the total energy stored in the field, $\frac{1}{2} LI_0^2$, would be:

$$\xi = \frac{R_D}{R_D+R_m} . \qquad (2.$$

Using the linear model, $R(t) = \gamma t$, the solution to the circuit equation:

$$I = I_o \, e^{-\frac{1}{L} (R_D t + \frac{1}{2} \gamma t^2)}$$

gives a dumping efficiency:

$$\xi = 2\beta e^{-\beta^2} \int_{\beta}^{\infty} e^{-\chi^2} \, d\chi, \qquad (3.$$

where $\beta = R_D/\sqrt{L\gamma}$. To estimate the efficiency of a dump one must know γ, which is dependent on thermal as well as electrical properties of the magnet. The dependence of ξ on circuit parameters, including γ, can be seen in Figure 3.

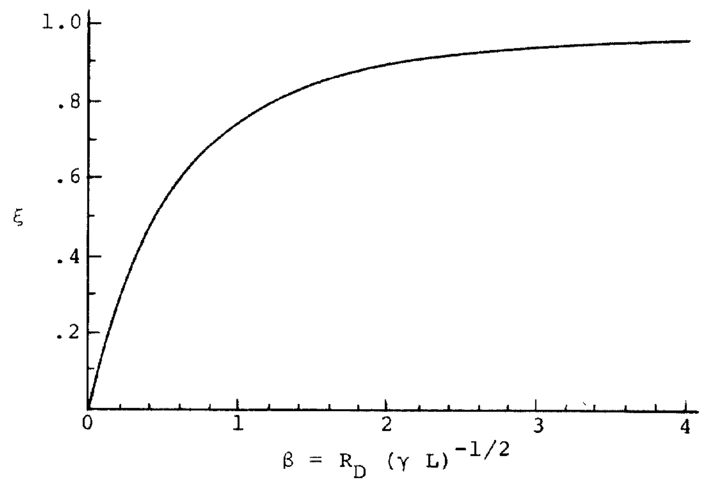

Fig. 3. Dependence of energy dumping efficiency, ξ, on various circuit parameters for the resistive dump of Fig. 1a and Equation (3.

Either of the dissipation circuits shown in Figure 1b and 1c, or any of the ones described by Watrous[9], can be used for the E.S. element of Figure 1d, the transformer coupled dump. For simplicity, a simple resistor was used. R_2, the total secondary resistance, included the on resistance of the SCR switch S, when used, and the self resistance of the copper secondary windings at 4.2K. The case of $\gamma = 0$ has solutions to the coupled circuit equations:

$$L_1 \frac{dI_1}{dt} + (R_D + \ \ t)I_1 + M \frac{dI_2}{dt} = 0 \qquad (4.$$

and

$$L_2 \frac{dI_2}{dt} + R_2 I_2 + M \frac{dI_1}{dt} = 0 \qquad (5.$$

of

$$I_1 = A_1 \ e^{f_1 t} + B_1 e^{f_2 t} \qquad (6.$$

and

$$I_2 = A_1 (e^{f_1 t} - e^{f_2 t}), \qquad (7.$$

where A_1, B_1, A_2, f_1 and f_2 are of form $f(R_D, L_1, R_2, L_2, k, I_o)$. The standard definition for coupling constant,

$$k = M/\sqrt{L_1 L_2}$$

is used. The dumping efficiency of the secondary for this case ($\gamma = 0$) is:

$$\xi = \frac{k^2}{1 + \frac{\tau_1}{\tau_2}} \qquad (9.$$

where $\tau_1 = L_1/R_1$ and $\tau_2 = L_2/R_2$ are time constants for the primary and secondary windings. An exact solution of Equations (4. and (5. for the case $\gamma \neq 0$ is not trivial, but if R_D remains much larger than $R(t)$ throughout the energy dumping cycle, this equation gives a reasonable estimate of efficiency. Plots of ξ (normalized to k^2) versus τ_1 are shown in Figure 4. It is evident from the expression and Figure 4 that, besides k approaching 1, high dumping efficiency requires $\tau_1 << \tau_2$. If this condition is met, then the current in the primary will go to zero very quickly, and the secondary will rapidly peak and then take a long time to decay. Invariably achieving $\tau_1 << \tau_2$ requires that R_2 be as small as possible.

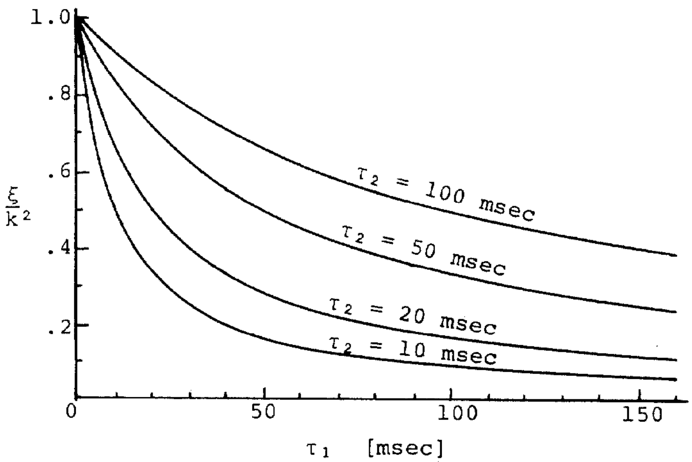

Fig. 4. Dumping as a function of primary and secondary time constants for a transformer coupled circuit in the case of $\gamma = 0$.

Equation (9. specifies only the fraction of total energy deposited in R_2. In practice, some sort of energy absorbing circuit will also be required across the primary in order to control terminal voltage. The total energy removal efficiency of the system will then be the sum of the fraction dumped in R_2 and the fraction dumped in the primary, here into R_D. An alternative to R_D, possible with SCR supplies, would be to use the quench detection circuit to switch the power supply to full invert, which would place a fixed voltage, of polarity reversed from normal, across the magnet terminals.

Model Testing

All testing was performed using a 2½-foot long Energy Doubler prototype magnet. Designated 2½ #3, it was wound with 3 layers of superconducting wire composed of ∿ 2300 NbTi filaments imbedded in a solid copper matrix.[2] A four-turn secondary was fashioned from 0.5 by 0.031 inch copper strips wound into a saddle coil with the long length on the horizontal midplane of magnet #3. Both primary and secondary windings were brought out of the helium dewar using vapor cooled power leads. Electrical characteristics were measured to be $L_1 = 7$mH, $L_2 = 12.2\mu$H, $R_2(4.2K) \simeq 300\mu\Omega$ and $k = .74$.

The electrical system, which is used for all Energy Doubler magnet testing, is shown in Figure 5, and a block diagram of the quench detection, or safety circuit, can be seen in Figure 6. The safety circuit, which is built in a standard 2-wide NIM module, amplifies the magnet terminal voltage and voltage from a pick-up coil mounted on the magnet. The difference, $L\,di/dt - d\phi/dt = IR(t)$, is monitored with a voltage comparator that can be set to detect a departure from zero of the IR(t) voltage corresponding to a developing resistance $R(t) < 1m\Omega$.

Tests 1 and 2 of Table I were done using only the Transrex's main contactor to shut down output power. This delays system response to the quench and produces more internal heating. As expected, the total efficiency during snap-off was the same as for tests 2, 4, 6 and 8. Tests 3 and 4 are done in the same configuration as 1 and 2 except that the firing pulses of the Transrex are electronically clamped to zero. This changes supply response from ∿ 100mS with the contactor alone to ∿ 8mS with the electronic clamp. In comparing transformer coupling tests 5 and 6, using an SCR switch in the secondary, with tests 7 and 8, which is a shorted secondary with no switch, it is evident that the "On" resistance of the SCR's lowers the dump efficiency of the secondary. In fact, the internal resistance of the secondary alone is not low enough to produce a secondary dump efficiency greater than ∿ 14%. This can be compared to a ξ, computed from Equation (9. and the transformer characteristics ($\gamma = 0$), of ∿ 25%.

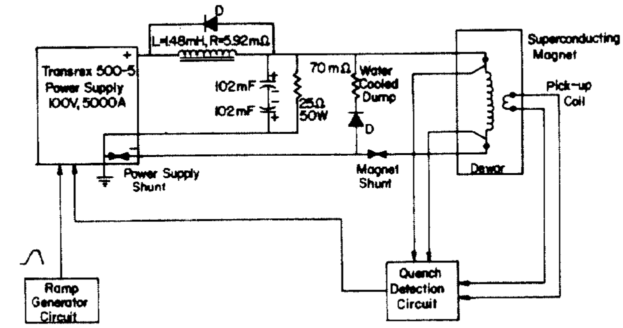

Fig. 5. Superconducting magnet electrical test circuit including quench detection and external resistive energy dumping.

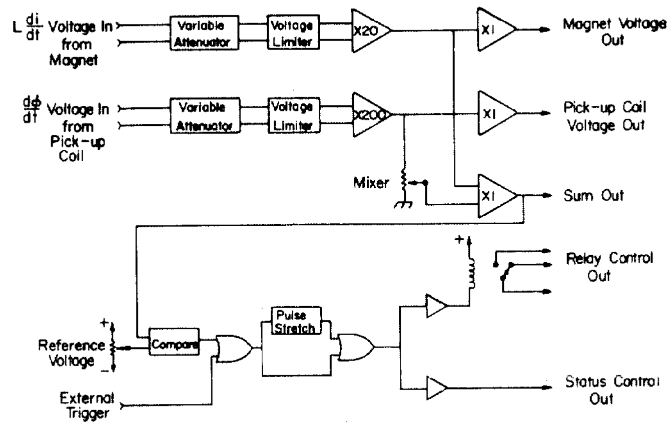

Fig. 6. Block Diagram: Superconducting magnet quench detection circuit.

Sample curves of current and energy dissipation versus time are shown for tests 3 and 7 in Figures 7 and 8. The ripple is caused by a problem with Transrex shutdown in which the output SCR's do not commutate off right away. This lowers dumping efficiency somewhat and will be eliminated in the near future.

Epilogue and Prologue

These preliminary studies have served to clarify some of the problems associated with protecting superconducting magnets during a quench. Transformer coupling does not seem likely to ever operate at useful efficiencies in Energy Doubler magnets. External dump resistors are quite effective and the voltages developed are not a problem in our magnets. Tentatively, it would appear that the circuit of Figure 1b, used as the E.S. element in the array of Figure 2, is the most promising way of accomplishing the parallel dissipation of field energy. However, many of the questions raised

TABLE I. SUPERCONDUCTING MAGNET ENERGY DUMPING, REPRESENTATIVE DATA FROM VARIOUS CIRCUIT CONFIGURATIONS

TEST	CONFIGURATION[1]	TRIGGER MODE	ENERGY DISSIPATED[2]				MEAS.	MEAS.
			TOTAL (W_T)	MAGNET (W_m)	R_D (W_D)	2ndary (W_2)	ξ	γ
1	Ext R_D No 2ndary	Quench	13.8	7.97	5.79	-	42%	28.9
2	No SCR Clamp	Snap-Off	13.2	3.86	9.32	-	71	4.3
3	Ext R_D No 2ndary	Quench	9.74	2.26	7.46	-	77	4.1
4	PS SCR Clamp	Snap-Off	9.40	1.87	7.53	-	80	2.1
5	Ext R_D 2ndary Trig'd	Quench	12.1	3.33	7.61	1.21	74	3.9
6	PS SCR Clamp	Snap-Off	9.5	1.34	7.15	1.01	86	1.2
7	Ext R_D 2ndary Short	Quench	13.1	3.91	7.50	1.78	71	4.9
8	PS SCR Clamp	Snap-Off	11.9	2.85	7.50	1.64	77	3.1

1. External Primary (Superconducting Winding) Dump Resistor R_D = 144 mΩ, all tests.
2. Kilojoules.

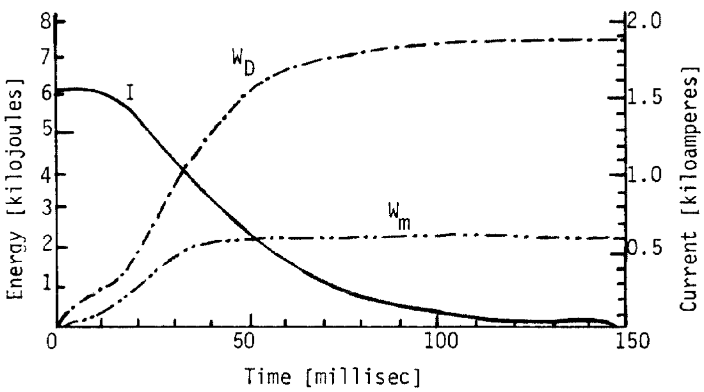

Fig. 7. Current and energy dissipation versus time for Test 3, Table I, primary dumping resistor and no secondary winding.

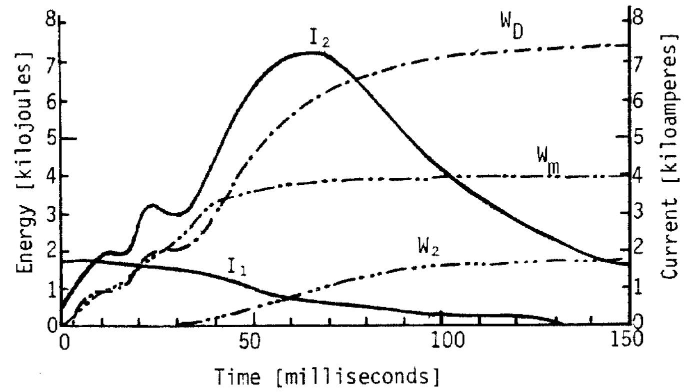

Fig. 8. Current and energy dissipation versus time for Test 7, Table I, transformer coupled dissipation into a shorted secondary winding.

remain to be answered. We expect shortly to test a dumping scheme wherein the Transrex is thrown into hard invert by the quench detector. This mode of controlling system terminal voltages is the most likely to be used in the Energy Doubler because it is compatible with existing Main-Ring power supply modules. It is hoped that SCR's can be found to perform as fast switches at ~ 20K. Power diodes with metal and ceramic structures have already been run in liquid nitrogen at 78K. Finally, detailed computer computations of normal zone propagation in Energy Doubler magnets will be carried out in order to obtain an estimate of the tolerance of these magnets to quenches.

Acknowledgements

The authors would like to thank E. Ioriatti and W. Habrylewicz for their dedicated help in carrying out the tests.

References

1. S.C. Snowden, "Fermilab Energy Doubler Magnets - Magnetostatics," IEEE Trans. Nucl. Sci. NS-22 (1975)

2. D. Drickey, R. Flora, B. P. Strauss and D. F. Sutter, "Performance Studies of Superconducting Dipoles for the Fermilab Energy Doubler," ibid.

3. Z. J. J. Stekly, "Theoretical and Experimental Study of an Unprotected Superconducting Magnet Going Normal," Advances in Cryogenic Engineering, Vol. 8, 585, Plenum, N.Y., N.Y.

4. L. Cesnak and J. Kokavec, "Study of the Propagation of the Normal Region in a Superconducting Solenoid," Cryogenics, 12, 116 (April 1972).

5. J. G. Cottingham, "Analysis of a Quench Event in the 20-inch Nb-Ti Magnet Model Constructed by G. Danby," Tech. Report BNL 18153, CRISP 73-13; Brookhaven National Laboratory; Aug. 15, 1973.

6. R. W. Boom and L. D. Roberts, "Study of the Transition of Small Niobium-Zirconium Superconducting Solenoids to the Normal State," J. Appl. Phys, Vol. 34, No. 8, August 1963, pp 2422-2425.

7. P. F. Smith, "Theoretical and Experimental Aspects of Superconducting Coil Protection," Review of Scientific Instruments, 34, 368 (1963).

8. M. W. Dowley, "Field Energy Removal from a Superconducting Solenoid," Cryogenics, 4, 153 (1964).

9. D. L. Watrous, "SCR Switch Aids Protection of Superconducting Coils," IEEE Trans. on Magnetics, Vol. MAG-1, No. 4, 402 (1965).

10. P. H. Burnier, J. Moreau, G. Vassal, M. Delume and C. Tram, "Device for the Transition Detection in Superconducting Coils," Advances in Cryogenic Engineering, Vol. 15, 190 Plenum, N.Y., N.Y. (1969).

11. B. J. Maddock and G. B. James, "Protection and Stabilization of Large Superconducting Coils," Proc. of the IEEE, Vol. 115, No. 4, April 1968, pp 543-547.