IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981
1981 Particle Accelerator Conference, Washington, D.C., March 11-13, 1981.

MAGNETIZATION CHARACTERIZATION STUDY FOR THE ENERGY SAVER/DOUBLER* DIPOLES

A. D. McInturff and D. Gross
Fermi National Accelerator Laboratory+
Batavia, Illinois 60510

ABSTRACT

One of the challenging problems in superconducting accelerator dipoles is their dynamic behavior under ramping magnetic field produced loads. Their behavior can be observed with hysteretic measurement of the energy flow in the magnet. This technique, first described in detail by M.N.Wilson, will determine changes in inductance, deflection of coils, dynamic losses, the superconducting cable's critical current vs. field and coupling curves, and iron shield saturation reproducibility. These measurements, when cross correlated with integral field, NMR and harmonic data yield a comprehensive characterization of the magnet. Data are presented for several magnets tested in the Magnet Test Facility of Fermilab. Measurements of inductance changes of a few percent and deflections of a few one-one thousandths of an inch are given. These data can now be routinely obtained on a production basis, therefore yielding a more complete characterization of the accelerator dipole's dynamic behavior.

INTRODUCTION

One of the fascinating problems in superconducting accelerator magnets is their dynamic behavior while producing magnetic fields which result in time varying loads. A straightforward technique with which these observations can be made involves the hysteric measurement of energy flow in and out of the magnet. The technique first described by M.N.Wilson[1] enables one with some slight extension to determine the magnet deflection under load, dynamic loss, the conductor's superconducting $J_c(H)$ "critical current as a function of applied field" and coupling characteristics, and the "Fe" shield saturation reproducibility. These data, when cross correlated with ∫Bdl, NMR (transfer function) and several other measurements allow a comprehensive characterization of the magnet and its components.

The circuit diagram used in these hysteresis measurements is shown in Figure 1.

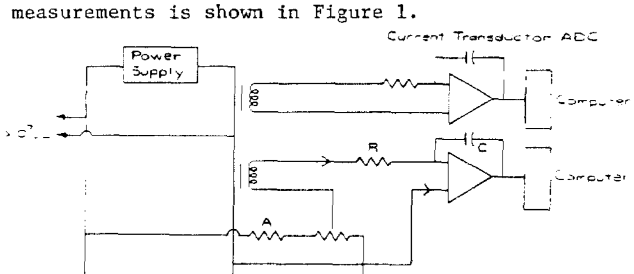

Fig. 1. Circuit used to measure energy in minus energy out in the E/S doubler ring magnets.

*A 1 TEV super conducting proton synchrotron under construction.
+Operated by Universities Research Assn., Inc., under contract with the U.S. Department of Energy.

The variable resistor (A) should have some type of voltage compensation to offset any thermal EMf. resulting from the transition of the voltage taps from the cold dewar environment to the electronics. It should be noted that great care must be taken in the establishment of a single ground in the circuit (including both the circuit being measured and the one performing the measurement). The combined impedences of all on the instrumentation that interfaces directly with the magnet being measured should be on the order of 10^7 Ω or greater. The data are stored in the computer as a digitized output of the integrator as a function of current/turn of the magnet. This data can be graphically displayed on a cal-comp plotter or graphics terminal for previewing.

THEORY

A super conductor, as a result of its infinite conductivity and resistance to flux flow can generate non-decaying eddy currents when it is subjected to changing magnetic fields. These "magnetizations" of the super conductor during cycling of a magnetic field are proportional to the loss curves measured by the integrator's signal or a portion of it. The integrator output as a function of magnet current (the area enclosed by a full cycle $0 \rightarrow I_{MAX} \rightarrow 0$) is given by

$$\text{Area} = \int dI \int \left(\frac{dt\ (fV - L_m \frac{dI}{dt})}{(\text{integrator time const.})} \right)$$

$L_m \frac{dI}{dt}$ is the signal from the mutual inductor

$f \equiv L_m / L_{magnet}$ (normal)

The loss signal is on the order of 10^3 smaller than the ramp voltage of a dipole magnet. It can be shown that the hysteretic loss curve of the magnet is proportional to the magnetization loop of the super conductor times an averaging (average amplitude in winding) constant.

In Figure 2 typical magnet type of loss curves are shown schematically.

If the inductance of the winding is changing as a function of current then the dashed curves would represent the resultant shape. The areas are, however, equal that are enclosed by the dashed curves and the solid curve. The solid curve represents an absolutely rigid E/S doubler dipole without an iron shield.

The forces which are present in a dipole magnet when it is being energized are normally such that the inductance increases. These Lorentz type forces should produce a distortion that has a curvature proportional to I^2. The curves are normally analyzed for a form which is given by $A + BI^2$.

The loss curve can be calculated from knowledge of the voltage divider and integrator circuit values and is double checked by placing a bar of metal of known resistivity in the bore of the magnet thereby acting as a shorted secondary during a magnet cycle.

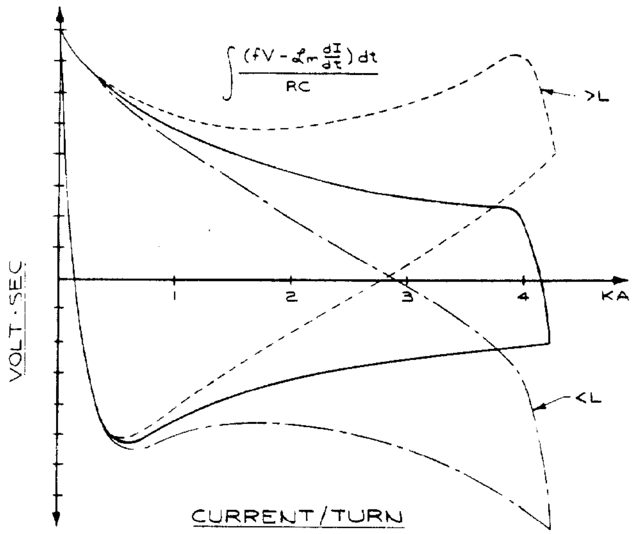

Fig. 2. Schematic drawing of various parameters' effect on the magnetization curve. (Note solid curve is magnetization as calculated from E/S Doubler Conductor.)[2]

The iron shield, which while in the infinite "μ" magnetic field range acts as a mirror for the coil package, will cause a decrease in inductance as the Fe becomes saturated (i.e., μ becomes finite).

The loss as a function of frequency can be formulated in two forms; first, the total loss as a function of $\dot{B}$ and, second, parametrically the loss as a function of $\dot{B}$ for a given current.

These loss data can be analyzed to provide a determination of the effective transverse resistivity of the cable.

The magnetization of a "Rutherford style" compacted cable conductor such as the one used is given by:

$$M = \frac{2\mu_o \lambda J_c d}{3\pi}\left\{1 + \frac{1}{\lambda J_c d}\left(\frac{\dot{B}\ell^2}{\rho_e} + \frac{\dot{B}_\perp L^2}{\rho_c}\left(\frac{2\pi d^2}{5} + \pi/2\right) + \frac{\dot{B}_\parallel L^2}{\alpha^2 \rho_c}\cdot\frac{3\pi}{8}\right)\right\}$$

$$\frac{2\mu . \lambda J_c d}{3\pi} = \text{filament magnetization}$$

$d \equiv$ filament diameter
$J_c \equiv$ critical current density
$\lambda \equiv$ filling factor
$\rho_e \equiv$ transverse composite resistivity
$B \equiv$ applied magnetic field
$\ell \equiv$ 1/4 composite stand transposition (twist rate)
$L \equiv$ 1/4 cable transposition (twist rate)
$\rho_c \equiv$ average effective transverse cable resistivity

Experimentally, it is possible to determine when the cable magnetization is comparable to that of the basic filament loss. These data will determine the effective transverse resistivity of the cable for cross strand coupling. It is also possible with the above expression to analyze the magnetization data to determine various $\dot{B}$'s at which the filament to filament and strand to strand coupling losses become comparable to the basic superconductor filament volume.

magnetization loss.

EXPERIMENTAL RESULTS

Data as received and plotted on a graphics terminal is shown in Figure 3. These data are for a typical Energy-Saver doubler cycle to 4.4 T on a 22 second ramp to full energy. This Magnet #384 represents a higher loss magnet with a more typical energy being 550 j/§ but is a good example to use to illustrate variations in the ramp rate dependences and the variations of the coupling term parameters. The droop of the hysteresis curve in Figure 3 has been analyzed with the results given in Table 1.

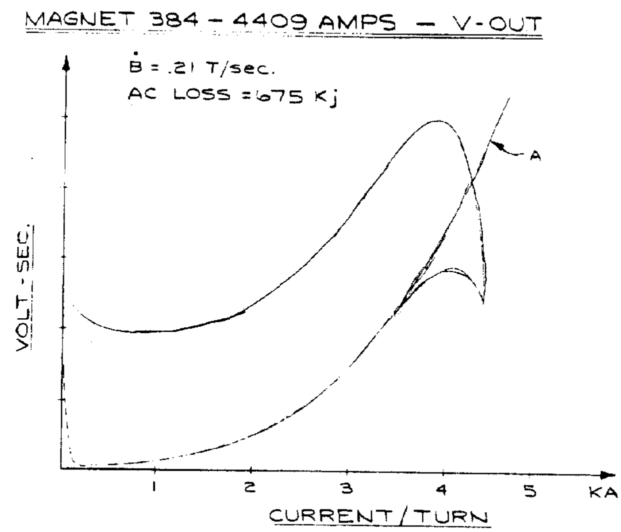

Fig. 3. Energy in minus energy out graphical plot of integrator output signal.

Table I

Inductance Changes
Magnet #384

L (Nominal)=42mH

Current Turn (kA)	Field T	ΔL(mH)
1.25	1.250	0.02
2.0	2.000	0.076
3.0	3.000	0.266
4.0	4.000	0.621
4.4	4.399	0.819

Figure 3 also clearly shows the effect of iron saturation distorting the magnetization above 3.8T.

Figure 4 represents the data as seen after the deflection of the magnet has been removed. These data were taken from the test of Magnet #417. It can be seen that a cross coupling of strands in this magnet becomes apparent about 0.9T (9kA). At 2.8T the coupling losses are already equal to the basic filament loss. The effective transverse resistivity of the cable would be $3\text{x}10^{-4}\Omega$-m at that point.

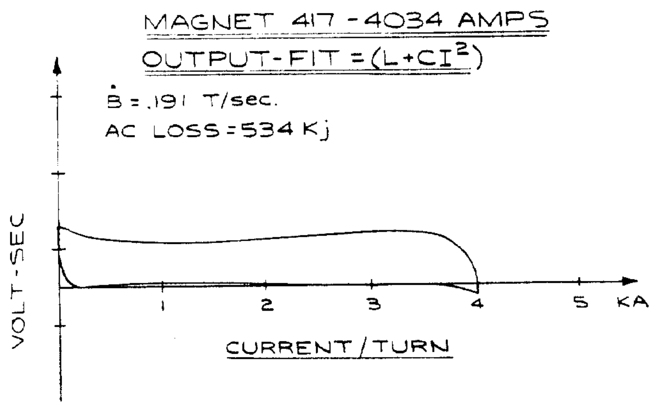

Fig. 4. Energy in-energy out with the average curvature (due to inductance change) removed.

In Figure 5 it is apparent that the 20% increase in losses in Magnet #384 versus Magnet #417 is attributable to the field at which the onset of the coupling occurs. With the exception of the field onset, the behavior of both magnets seems identical.

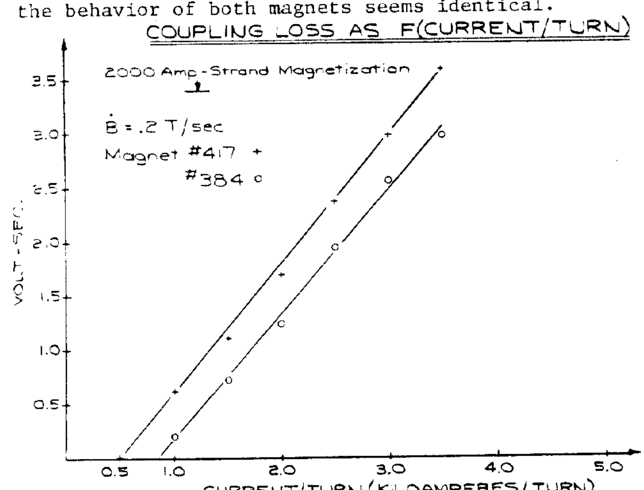

Fig. 5 is a plot of the energy loss in excess of the Conductor Magnetization (filament) loss as calculated[2]. A relatively higher loss magnet is compared to an average loss one.

Table II gives the loss at 3.3T as a function of Ḃ for the two magnets (numbers 384 and 417).

Table II

Magnetization of Magnets As Function of Ramp (J/ϕ)
Peak Field = 3.3T

Ḃ T/sec / Magnet	# 384	417	267	Quad
.099		333		94
.121			446	
.153	434		467	
*→ .195		366		
*→ .224			462	
.308		423	462	94
.488	533			
.733	604			

*Near Operational Ramp E/S Doubler

Table III shows the threshold effect for the coupling loss, that is to say, there is a minimum rate at which the field may be ramped that below which the losses are essentially constant. This level commonly referred to as the basic superconductor filament loss.

Table III
Magnetization of a Magnet as a Function of Ramp
Peak Field - 2T
*E/S Doubler Ramp

Ḃ T/sec	Joules Cycle	Dipoles	Quad
.055	196	247	55
.103	192	241	
.159	210		
*→ .202	229	260	60
.320	233	270	
.390			65
.510	261	300	

These data indicate that a half ramp rate would lower the refrigeration load to ∿40% of that of the standard cycle.

Utilizing the parameters of the cable strand, the estimated Ḃ that the strand coupling loss becomes comparable to the basic filament magnetization is 0.6T/sec, while that for strand to strand coupling at 4.T is 0.2T/sec.

CONCLUSIONS

It is possible to now routinely obtain data that enables all of the aforementioned parameters to be determined in the same amount of time on the test stand that the old A.C. loss data was taken at the FNAL Magnet Test Facility. According to the specific model taken, the changes of inductance found would indicate a deflection of the coil of 60÷100 micron during the ramping of the magnetic field.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to K. Ishibashi for his calculations of the magnetization curves.

References

[1]M.N.Wilson, CRYOGENICS, June, 361, (1973).
[2]K.Ishibashi, private communication, 1980.