PULSE LOSS AND VOLTAGE MEASUREMENTS ON SUPERCONDUCTING MAGNETS*

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29

ABSTRACT

This paper describes an electrical method for measuring pulse losses and compensated voltage in superconducting magnets. Test results from two pulsed solenoids are recorded and analyzed digitally by computer. Dependence of loss performance on $B_{\max}$ and $\dot{B}$ is studied. The effects of conductor motion and presence of normal metal on the loss performance are also discussed.

I. INTRODUCTION

The poloidal systems of the Experimental Power Reactor (EPR) require fast flux swing (~ 7 T/sec) at high field (~ 7 T) during part of the operation cycle. A diagnostic tool is needed for testing the pulsed magnets of the systems and understanding the associated loss phenomena. Such a tool has been developed by Wilson¹ based on the shape and area of the hysteresis loss loop. However, additional information about the loss mechanisms could be obtained if the loss voltage waveform due to flux change inside the conductor is monitored and calibrated.

Our method is based on analysis of the voltage waveform. The method of calibration is discussed in detail below. Besides providing insights into the loss mechanisms, the calibrated loss voltage is believed to be the most sensitive signal for detecting any instability, such as flux jump or mechanical motion, and can be used for reliable quench detection and coil protection.

This paper presents experimental results of pulse loss measurements for two solenoids operated under conditions similar to those in EPR. Main parameters of the solenoids are given in Table I.

TABLE I
Main Parameters of Two Pulsed Solenoids^a

	Magnet I	Magnet II
Bore, cm	5.1	5.1
Length, cm	23.4	15.5
Inductance, H	0.096	0.131
Maximum Field, T	7.2	5.2
Stored Energy, kJ	31	12
Conductor	27 strand, braided Cu matrix	35 strand, braided Cu matrix
Winding Scheme	Potted	Tightly wound

^a Designed by M. S. Lubeil and fabricated by W. J. Schill at ORNL.

II. MEASUREMENT SCHEME

A schematic diagram of our measurement system is shown in Fig. 1. The ΔV in Fig. 1 represents the com-

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pensated loss voltage due to the flux change, $d\phi_0/dt$, inside the superconductor. All flux change outside, $d\phi_{\text{ext}}/dt$, is compensated by using Rogowski coil. The criteria for obtaining a perfect compensation are given in Section III.

Loss can be calculated with either of the following two equations:

$$Q = \frac{1}{K_0} \int \Delta V I dt \text{ (J/cycle)}, \quad (1)$$

$$Q = \frac{1}{K_0} \int \Delta V dt dI \text{ (J/cycle)}. \quad (2)$$

The ϕ -I curve of the magnet can be obtained from Eq. (2). Each of our test cycles consists of changing the current from zero to maximum and back to zero again. It should be noted that the cycling history will strongly affect both the value of Q and the shape of the ϕ -I curve.

III. ANALYSIS

General

It has been proved¹ that the integral of the compensated voltage signal is equal to

$$\int_0^t \Delta V(t') dt' dI = \sum_i \int \mu_0 M_i dH_i f \Delta v_i \quad (3)$$

since $\phi_0(t) = \int_0^t \Delta V(t') dt'$, from Eq. (3)

$$\phi_0(t) = \sum_i \mu_0 M_i h_i f \Delta v_i, \quad (4)$$

where $h_i = H_i/I$.

Shielding Region

For very small transport current, superconductor regions behave like a perfect diamagnet. Hence

$$M_i = -2H_i,$$

where the factor of 2 is due to the demagnetization effect of a filamentary conductor in the presence of perpendicular magnetic field. Therefore,

$$\phi_0(t) = - \frac{2If}{\mu_0} \sum_i b_i^2 \Delta v_i, \quad (5)$$

where $b_i = \mu_0 h_i$. Since all the quantities on the right side are known, Eq. (5) can be used to calibrate the compensation. This equation should hold regardless of the $\dot{B}$ used, provided that the coupling loss is still negligible. Figure 2 shows a typical ϕ_0 -I curve where Eq. (5) represents the initial linear region.

Remanent Flux

Flux is trapped at the end of each test cycle. As shown in Section IV, different test cycles end in the same amount of trapped flux, provided their maximum currents all exceed a certain threshold. Let I_r denote the corresponding remanent magnetization. Eq. (4) gives for $I = 0$ at the end of the cycle

$$\phi_0(I=0) = \mu_0 M_r f \sum_i h_i \Delta v_i. \quad (6)$$

This equation could be used to predict the value of M_r .

Differentiating Eq. (4), the loss voltage can be expressed as

$$\Delta V(t) = \sum_1 \mu_0 f \frac{dM_1}{dH_1} \frac{dH_1}{dt} h_1 \Delta V_1, \quad (7)$$

If the family of short sample M-H curves is available, voltage can be predicted by Eq. (7). A typical compensated voltage waveform is shown in Fig. 2.

Normal Metal Loss and Conductor Motion

The loss voltage signal should reflect any normal metal circuit present through their mutual inductive coupling to the magnet. Therefore, eddy loss in the normal metal can be measured. Experimental results of loss with the presence of copper rod are given in Section IV.

Conductor motion will offset the compensation and hence will result in abnormality of the loss voltage waveform and the ϕ -I curve. This phenomenon is clearly observed in the unpotted magnet (Magnet II).

IV. RESULTS AND DISCUSSION

Magnet I

Hysteresis Losses. For slow cycling (< 0.1 T/sec) transport current, the measured hysteresis losses per cycle are given in Fig. 3. Similar to short sample results, it clearly shows two different transport current-dependence regions. In the I^3 region, most filaments are not yet saturated by the external field, whereas the I linear region represents completely penetrated flux-flow region. Figure 4 shows a sequence of ϕ -I curves for monotonically decreasing peak value of ramp current. Figure 5 shows the same series for smaller currents (< 200 A).

Normal Metal Effect. In order to demonstrate normal metal coupling effect, a 13-cm-long cylinder of Cu with a volume of 1.45×10^{-4} m³ ($\approx 50\%$ of Cu matrix in the magnet winding) is placed inside the magnet bore. As the magnet is cycled, eddy current losses induced in the Cu cylinder are measured together with the loss in winding. Figure 6 shows the results. The peak value of the ramp current is 400 A corresponding to 4T at center of the magnet. The fastest ramp speed shown in the figure is about 0.6 T/sec. Figure 7 shows a comparison between two ramp cycles with and without normal metal coupling circuit. The difference of the areas is due to the eddy current losses in Cu.

Discharging Test. Discharging test results are presented in Fig. 8. Measured losses for slowly charging up, then quickly dumping are plotted vs discharge time constant. The results have shown that the magnet can be discharged from 6.2 T at a rate of 10 T/sec without going normal. This may be a viable scheme for operating ohmic heating coils in a tokamak fusion reactor.²

Magnet II

Hysteresis Loss. Measured hysteresis losses per cycle for this tightly wound magnet are presented in Fig. 9. The I^3 dependence region is clearly shown. For current higher than 150 A (2 T at conductor), conductor motion was detected. Figure 10 gives corresponding voltage waveform and ϕ -I curve. Note that the voltage increase during the charging period implies that conductor motion offsets the compensation and thus causes distortion in ϕ -I curve shape.

It has been shown that the electric method of loss measurement can yield not only the total energy loss but also the compensated voltage waveform. Methods of its compensation and its application as a diagnostic tool for magnets are demonstrated. Theoretical formulas for voltage waveform in terms of the short sample characteristics are also given. Quench detection and protection schemes for multi-coil magnet systems in a tokamak fusion reactor have been designed based on this method of loss voltage measurement.³

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NOMENCLATURE

- $B_{\max}$ - Maximum magnetic induction on conductor, T
- $\dot{B}$ - Rate of change of the magnetic induction, T/sec
- ϕ_0 - Flux inside conductor region, Wb
- ϕ_{ext} - Flux outside conductor region, Wb
- Q - Loss per cycle, J/cycle
- K_0 - Attenuation or amplification factor
- ΔV - Compensated loss voltage ($= d\phi_0/dt$), V
- I - Transport current in magnet, A
- M - Magnetization, A/m
- M_r - Remanent magnetization, A/m
- H - Magnetic field strength, A/m
- ΔV_1 - Volume of the i -th element of the magnet winding, m³
- f - Fraction of superconductor in magnet winding
- b_i - Magnetic field induction at the i -th volume element produced by unit transport current, T/A
- h_i - b_i/μ_0
- τ_0 - Effective time constant for unsymmetrical ramp current, sec
- τ_d - Magnet discharge time constant, sec

- (1) Q (Joules/cycle) $\approx \frac{1}{\omega_0} \int |V_0| dt$
- (2) Q (Joules/cycle) $\approx \frac{1}{\omega_0} \int |\Delta V| dt$
- (3) Q (Joules/cycle) $\approx \frac{1}{\omega_0} \int (I / \Delta V) dt$

Fig. 1. Schematic diagram of loss measurement system.

Fig. 2. Typical test current, and compensated voltage waveform and ϕ -I curve.

Fig. 3. Hysteresis losses vs transport current for Magnet 1.

Fig. 4. Series of ϕ -I curve for monotonically decreasing amplitude of pulsing current - Magnet 1. Fig. 5. Series of ϕ -I curve for monotonically decreasing amplitude of pulsing current - Magnet 1.

Fig. 6. Measured loss per cycle vs $1/\tau_0$ for Magnet 1.

Fig. 7. B-I curve comparison for Magnet 1 with and without Cu inside the bore.

Fig. 8. Measured loss per cycle vs $1/\tau_0$ for Magnet 1.

Fig. 9. Hysteresis losses vs transport current for Magnet II.

Fig. 10. Current waveform, compensated voltage and B-I curve for Magnet II showing conductor action.