A STUDY OF EDDY-CURRENT EFFECTS IN THE STRUCTURE OF THE WESTINGHOUSE LCT COIL*

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Abstract

One of the six 2.5- x 3.5-m-bore 8-T superconducting magnets of the international Large Coil Task (LCT) was designed and fabricated by Westinghouse Electric Corporation with the oversight of Oak Ridge National Laboratory. This coil, designated WH, has a mechanical structure composed of a stack of aluminum plate segments held together with stainless throughbolts. When the magnetic flux through the coil is changed, voltage is induced in the structure, and to avoid excessive currents the design provided low-voltage insulation between plate segments. However, during construction it appeared that this anodizing layer may have been breached extensively. Electrical tests on delivery confirmed this, and supplemental instrumentation was added to the structure before the coil was installed in the test facility. The shorting raised concerns about increased refrigeration load, local overheating, and a change in dump characteristics. After installation, current ramps to 5 A showed magnetic diffusion time constants of 1.5 s at room temperature and 3.0 s at 20 K, an order of magnitude larger than for the other LCT coils. These latter coils have structural cases of stainless steel, which has an electrical resistivity 17 times that of the 2219-T87 aluminum used in the WH coil. In tests at operating currents, temporal values of voltage, current, temperature, and energy distribution during ramp and dump agree with those values calculated on the basis that the aluminum structure is solid, and are quite different from values calculated without considering shorting. On dump, the coil is partially self-protecting, but 23% of the initial stored energy is deposited in the structure at cryogenic temperature. The various effects of the shorting are apparently tolerable for testing in the International Fusion Superconducting Magnet Test Facility (IFSMTF). For other cases, the coil designer should carefully consider if and how the structure should be electrically segmented.

Introduction

In the Large Coil Task, six separate design teams independently designed large superconducting coils for testing together in a compact toroidal array. They were to meet the same performance specifications; however, design diversity was sought to enlarge the test data obtainable. Five coils have stainless structural cases that enclose the winding pack. Westinghouse recognized several advantages to a segmented plate structure^{1,2} in which the conductors are embedded a few at a time. To reduce weight and cost, the test coil used aluminum plates rather than steel ones. To reduce the effects of eddy currents on change of current in the test or pulse coils, the plate segments were insulated by anodizing (Fig. 1). However, during fabrication it appeared to us that the insulation might have been breached extensively - by smearing of aluminum from one plate to another during line reaming of the bolt holes, by insertion of the uninsulated and tight-fitting throughbolts, and by miscellaneous metal work done after anodizing. It is

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Manuscript received September 30, 1986.

Figure 1. WH coil showing aluminum plate structure.

thought that such shorting mechanisms could be avoided in the future.

Possible deleterious effects of shorting among the plate segments were local and global. If the segments were shorted at many places, they would act as a shorted secondary of a transformer whose windings are magnetically very well coupled. If the coil were dumped, induced currents on the order of megamps would flow around the closed loop of the plate. If the shorting were more localized but still sufficient to give a closed metallic path encircling the coil axis, then the total induced current would be less but the current would be greatly concentrated at the constriction, and local hot spots would develop. For example, there could be a shorting from plate to bolt shank to adjacent plate through a half-dozen bolts in the region near the plate splits, where bolt shear loads are greatest. If so, each 7/8-in. A285 bolt would carry tens of kiloamps and would quickly overheat (hundreds of degrees Celsius). Thus during the five days between receipt of the coil and its placement in the vacuum vessel, it was necessary to determine if the plates were shorted and whether remedial measures were required (partial copper shield, welding plate edges to generalize the shorting, etc.).

After Arrival

Tests to See If Shorting Existed

Preliminary tests of the WH coil conducted after it was delivered to the IFSMTF showed that there was appreciable shorting of the plates, particularly through the bolts. Figure 2a is a trace of the coil voltage during discharge into an open circuit, after being charged to 750 mA. It indicates a time constant of about 1.5 s, much longer than that of any of the

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(a) 500 ms/div

(b) 50 μs/div
TIME

Figure 2. Open circuit discharges from 750 mA. (a) Westinghouse coil. (b) General Dynamics coil.

other coils. The peak potential reached about 0.6 V, and there was virtually no ringing other than a fast switching transient at the beginning of the discharge. By contrast, the warm General Dynamics coil produced an initial peak of 700 V and had a period of about 225 μs with damped ringing when discharged from 750 mA into an open circuit (Fig. 2b).

One of our primary concerns was the possible weakening of bolted joints caused by heating due to induced currents. To determine the magnitude of this heating during a dump, we connected opposing ends of selected bolts to the terminals of a differential oscilloscope by means of twisted shielded leads. The wires from the bolt ends were brought axially across the coil by the shortest path to minimize induced voltages in the instrumentation. The voltage across each bolt was measured as a function of terminal-to-terminal voltage. The highest voltage measured occurred at the ends of bolt B-13, located just below the upper break on the curved side. This measured 120 μV when the winding discharge reached a peak of 600 mV. The total resistance of this bolt at 4.2 K was calculated to be 1142 μΩ. A 2500-V dump during operation would therefore cause approximately 0.5 V to be developed between the ends of the bolt and produce 219 W of heating.

Table 1 shows the voltages measured between the ends of some of the bolts and the anticipated heating effect, assuming the voltage is applied only at the ends. This may not be an accurate representation, since the bolts are close fitting and were customarily hammered lightly for insertion during coil fabrication.

Circuit Model

A lumped-element circuit model as shown in Fig. 3 was used to predict the coil response during a dump. It has three inductively coupled L,R circuits. In this model each circuit may have some initial current at time $t = 0$, the moment when switch S is opened. The analytic solution was derived and used to predict currents and voltages of the LCT coils during ramps and dumps.

Table 1. Voltage Measurements of Bolt System.

Bolt Designation	Measured Voltage (V) (600 mV in coil)	Bolt Peak Power (W) (2500-V Dump)
B-12	80	97.3
B-13	120	219.0
B-14	33	16.6
B-15	25	9.5
B-16	20	6.0
B-17	3	0.14
B-18	10	1.5
B-19	16	3.9
B-20	20	6.0
B-21	17	4.4

Figure 3. Lumped-element circuit model.

For the simplified case of two circuits where the coupling coefficient is unity, the results are well known and summarized below. If

$$t < 0 \quad i_1 = I_m \\ i_2 = 0$$

then

$$0 < t \quad i_1 = \frac{\tau_1}{(\tau_1 + \tau_2)} I_m \exp\left(-\frac{t}{\tau_1 + \tau_2}\right) \quad (1)$$

$$i_2 = \frac{R_1}{R_2} \sqrt{\frac{L_2}{L_1}} \frac{\tau_1}{\tau_1 + \tau_2} I_m \exp\left(-\frac{t}{\tau_1 + \tau_2}\right) \quad (2)$$

$$\frac{Q_2}{Q_0} = \frac{\tau_2}{\tau_1 + \tau_2} \quad (3)$$

where

$$Q_0 = \frac{1}{2} L_1 I_m^2$$

$$Q_2 = \int_0^\infty i_2^2 R_2 dt \quad (\text{energy transferred to circuit 2})$$

$$\tau_1 = L_1 / R_1$$

Note that (a) at $t = 0$ the current i_1 in the energized

Figure 4. Low-current ramp test of the WH coil without dump resistor.

loop falls abruptly, and the flux is kept constant by a corresponding upward jump in i_2 , and (b) the fraction of magnetic stored energy transferred to the second circuit depends only on the time constants.

For the WH coil the initial ramp tests indicated that the coupling coefficient between plate structure and the embedded winding was very close to 1 and that the time constant of the structure was between 2 and 3 s at 100 K (see Fig. 4). Initial predictions were based on $\tau = 3.0$ s at 4 K. Figure 4 shows one ramp with $di_1/dt = 0.5$ A/s. If the coupling coefficient to the plates was not nearly unity, there would have been a step change in voltage when the ramp started. To obtain a more accurate value of the time constant, a dump from 11.4 kA was analyzed. The current showed an initial drop and then an exponential decay (Fig. 5) as predicted by Eq 1. A least-squares fit of I to the exponential after the initial drop gave a value of 9.4 s for the combined time constant. Since the coil (L_1) and dump resistor (R_1) give a time constant τ_1 of 7.2 s, the plate's time constant is $\tau_2 = 2.2$ s. The circuit values used to model a dump are given in Table

Figure 5. WH coil dump from 6400 A.

2. The approximation was made that the plate inductance equaled the coil inductance divided by the turns ratio squared. The plate resistance was then calculated from the time constant.

A Rogowski coil was installed around the outer leg of the WH coil of necessity encircling both winding and structure (and so measuring net current). Low-current ramps established the ratio of

$$C = \frac{V}{di/dt} = 0.0154 \text{ V/(A/s)} ,$$

which was consistent with the value calculated from the dimensions and turns of the Rogowski coil. In the numerical model the Rogowski coil voltage was predicted by

$$V_{\text{Rog}} = C \left(\frac{di_1}{dt} + \frac{1}{N_1} \frac{di_2}{dt} \right), \quad (4)$$

where subscripts 1 and 2 refer to the winding and structure (Table 2).

Table 2. List of Circuit Parameters.

Parameter	Value	How Obtained
WH coil inductance	$L_1 = 0.75 \text{ H}$	Measured
WH dump resistor	$R_1 = 0.104 \Omega$	Measured
Inductance of plate structure	$L_2 = 4.17 \mu\text{H}$	Assumed
Resistance of 2219-T87 Al plate structure	$R_2 = 1.9 \mu\Omega$	*
EU coil inductance	$L_3 = 1.57 \text{ H}$	Measured
EU coil dump resistor	$R_3 = 0.2248 \Omega$	Measured
Coupling coefficient from L_1 to L_2	$K_{12} = 0.99$	*
Coupling coefficient from L_1 to L_3	$K_{13} = 0.163$	Measured**
Coupling coefficient from L_2 to L_3	$K_{23} = 0.163$	Measured**
Number of turns in winding	$N_1 = 424$	Counted
Number of turns in structure	$N_2 = 1$	Assumed

* See text.

** Based on measured L_i and M_{ij} (mutual inductances). $K_{ij} = M_{ij}(L_i L_j)^{-1/2}$.

Figure 6. Rogowski coil voltage for 6400-A dump.

Figure 7. Hall probe response during ramp to 6400 A, followed by a dump.

Figure 8. Calculated plate current for the dump from 6400 A.

Comparison With Experiment

Figures 5 through 7 show a comparison of the experimental results during a dump and the calculated values based on the parameters in Table 2. The rapid

initial drop in coil current shown in Fig. 5 is accurately represented. If there was not a corresponding increase in plate current, then the Rogowski coil signal shown in Fig. 6 would have a very large initial transient, which is not present. The measured and calculated Rogowski coil signals show excellent agreement, proving the eddy currents are within the coil structure. A further confirmation is shown by Fig. 7, which is a plot of the field measured by a Hall probe in the inner edge of the coil bore versus coil current. For slow current ramps up or down, the field is linear with current as expected. During the dump, however, the field stays nearly constant as the current drops in the winding and increases in the plates. The calculated field value was obtained by assuming the field is given by

$$B = B_0 (i_1 + i_2/N_1)/i_{10}$$

where B_0 and i_{10} are the field and coil current immediately prior to the dump. It appears that the bandwidth of the data system was not high enough to follow the initial current transfer.

Figure 8 shows the calculated plate current, which peaks at 600 kA. For the dump from 11.2 kA, the plate current reached 1.0 MA and, if there was a full-current single-coil dump, the estimated peak is 2 MA.

The effect of the energy transfer to the plates was an increase in temperatures. The 6.3-kA dump raised the measured plate temperatures to approximately 20 K. Thermocouples installed on selected bolts did not show any change, probably since the temperatures remained too low for thermocouple measurement.

The induced eddy currents in neighboring coils agreed well with predictions based on the lumped circuit model.

Conclusions

The aluminum plate structure was inadvertently shorted to itself extensively enough that local hot spots due to eddy-current heating are probably not a problem. However, the 2219-T87 aluminum structure has an electrical resistance low enough that the overall influence of the shorting was quite apparent, and measured values of various parameters were in agreement with calculations that assumed complete shorting of the plates. Current ramps and dumps produced large circulating currents (up to 1 MA) in the plates, increased refrigeration losses, increased plate temperatures, and changed dump characteristics. These effects were all tolerable for testing in the IFSMTF but may be intolerable for tokamaks, especially those with pulsed fields. If so, the designers should use a higher resistivity structural material such as stainless steel, or consider hard anodizing after all machining, combined with aleeved bolts and great attention to detail.

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Received by OSTI
NOV 12 1986

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