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A COMPUTER CIRCUIT ANALYSIS OF INDUCED CURRENTS IN THE MFTF-B MAGNET SYSTEM

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A COMPUTER CIRCUIT ANALYSIS OF INDUCED CURRENTS IN THE MFTF-B MAGNET SYSTEM

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Summary

An analysis was made of the induced current behavior of the MFTF-B magnet system. Although the magnet system consists of 22 coils, because of its symmetry we considered only 11 coils in the analysis. Various combinations of the coils were dumped either singly or in groups, with the current behavior in all magnets calculated as a function of time after initiation of the dump.

As expected, results show that the effective current decay time constant of those magnets dumped is larger than the time constant anticipated in the dump of a solitary magnet, due to mutual coupling. The increased time constant leads to a slightly higher adiabatic temperature rise in the conductor during the dump, contrasted to the comparable rise in conductor temperature during dump of a solitary magnet. For example, this effect in the MFTF-B magnet system leads to a 3 to 7°K higher conductor temperature, depending upon the magnet and dump grouping. The peak induced current generally occurs some 60 to 200 seconds after dump initiation. In some magnets, the induced current is large enough — about 20% — to quench the conductor in the magnet.

Introduction

In the event of a dump of one magnet or group of magnets in a coupled multiple-magnet system, currents induced in those magnets not dumped could possibly lead to disastrous consequences. If the induced currents are large, the electromagnetic loads could become excessive, leading to structural failure. At least, the induced current might exceed the critical current limits in the nondumped magnets, causing a quench and consequent dump of the magnets.

It is of interest, therefore, to investigate the temporal behavior of induced currents in the dump of one or more magnets in a coupled multiple-magnet system. This paper deals with results obtained for the MFTF-B magnet system.

Figure 1 is a schematic of the 22 MFTF-B magnets. The 11 coils considered in our analysis are shown with their designations: seven solenoid coils (S1 through S7), transition coil (T1), two coils of the ying-yang pair (M1 and M2), and the A-cell coil (M3).

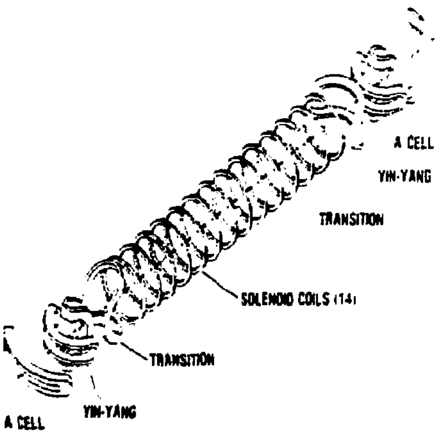

Figure 1. Schematic [illegible] magnets [illegible] MFTF-B

Computer-Aided Circuit Analysis

Our analysis of the induced current behavior of the MFTF-B magnet system used a commercial circuit analysis program, SYSCAP. SYSCAP is a system of circuit analysis programs that performs static, dynamic, and linear/nonlinear nodal analysis of electronic circuits.

Induced current behavior was calculated using the transient TRACAP operating mode of SYSCAP. Each of the 11 magnets was modeled by the circuit shown in Figure 2. All 11 circuits were similar; only the component values differed.

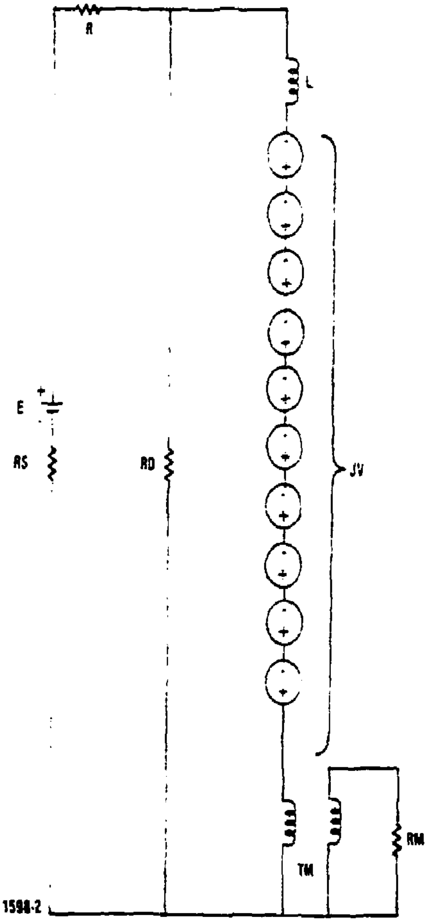

Figure 2. Each magnet was modeled by a circuit similar to that shown.

The power supply, E, was used simply to provide the initial operating current for the magnet. The power supply series resistance, RS, was chosen to be 9.9977 X 10^{-4} ohm so that the total resistance that the power supply sees is exactly 10^{-3} ohm. In this way, the power supply voltage is simply the operating current divided by 1,000.

The dump resistor, RD, has the appropriate value to give a maximum dump voltage of 1,000 volts for all magnets but the solenoids. The solenoid dump voltage is 200 volts.

The resistor, R, functions as a switching resistor to divert the current in the dumped magnet to pass through the dump resistor. The initial value of R was 10^{-8} ohm. As is explained later, this resistor is switched from 10^{-8} to 10^{7} ohm when it is desired to dump that particular magnet.

Magnet inductance is represented by the inductor, L. The resistance of each magnet was set at 10^{-7} ohm, which seems a reasonable value for a large superconducting magnet with a large number of splices within the winding.

Mutual inductance effects were modeled by current-dependent voltage sources, JV, with one source for each pair of coupled magnets. The internal resistance of each source was 10^{-8} ohm. The voltage of a given source, in the circuit of one of a pair of coupled magnets, is dependent upon the current in the resistor, RM, in the secondary of the one-to-one transformer, TM, in the circuit of the other magnet of the coupled pair. Further, the voltage is also directly dependent upon the mutual inductance between the pair of coupled magnets. The current in RM was determined by the voltage induced in the secondary of transformer TM. This voltage was determined by the transient current in the primary of TM, which is the transient current in the magnet itself. The inductance of the primary of TM was made 10^{-8} henry — small enough to not affect the Q of the magnet. The resistance of the secondary and primary coils of TM was 10^{-8} ohm.

A given magnet, or magnets, was dumped in the following fashion: upon dump initiation, all power supplies are switched off. At the same instant, the switching resistors of the magnets being dumped are switched from 10^{-8} to 10^{7} ohm. This forces the current in the dumped magnets to pass through their dump resistors and the magnets are discharged rapidly. Switching resistors of magnets that are not dumped remain unchanged; thus, currents in the magnets circulate through the outer loop of Figure 1 and begin a very slow decay due to the 10^{-3} ohm resistance in this circuit.

The value of RM was determined by employing SYSCAP to analyze a simple, two-coil case that could be treated analytically. The value of RM was varied until the induced current behavior calculated by SYSCAP exactly matched the results of the analytical calculation. The value of RM determined in this fashion was 9.8459 x 10^{-9} ohm.

Results

Operating current values for magnets within the MFTF-B magnet system are listed in Table 1 for the operating mode where the central, on-axis magnetic field is 1.0 Tesla. The table includes values of the operating currents. Table 2 presents the self- and mutual inductances of all magnets of the MFTF-B magnet system.

Table 1. Operating current of magnets in MFTF-B magnet system for a central field of 1.0 Tesla.

Coil	Operating Current (A)
M3	5,416
M2	5,207
M1	5,207
T1	6,431
S7	2,589
S6	2,631
S5	2,668
S4	2,668
S3	2,668
S2	2,668
S1	2,668

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We have analyzed the emergency dump of many different groupings of the MFTF-B magnet system. Space limitations preclude listing all results obtained. In some instances (e.g., dump of M3 only), the induced currents in the remaining magnets are virtually nonexistent because of the small coupling between M3 and the other magnets.

Tables 3 through 6 summarize results of dumping five different magnet groupings. The tables give the operating current, I_0, the induced

Table 3. Induced currents due to dump of two different solenoid [illegible]

Solenoid Grouping	Coil	Induced Current (A)		$\Delta I/I_0$ (%)	t_{peak} (sec)
		I_0	ΔI		
S1 - S7	T1	6,431	239	3.72	[illegible]
S1 - S6	S7	2,589	502	19.4	[illegible]

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Table 4. Induced currents due to simultaneous dump of M1, M2, [illegible]

Coil	Induced Current (A)		$\Delta I/I_0$ (%)	t_{peak} sec
	I_0	ΔI		
M3	5,416	64	1.2	[illegible]
S6	2,631	521	19.8	[illegible]
S5	2,668	94	3.5	[illegible]
S4	2,668	32	1.2	[illegible]

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Table 2. Self- and mutual inductances of MFTF-B magnets

Inductance (H)	Magnet Coil										
	M3	M2	M1	T1	S7	S6	S5	S4	S3	S2	S1
M3	10.6										
M2	0.162	[illegible]									
M1	0.0962	1.15	[illegible]								
T1	0.0157	0.131	0.316	3.44							
S7	0.0113	0.0456	0.0622	0.417	3.04						
S6	0.00683	0.0287	0.0361	0.166	0.647	4.31					
S5	0.00563	0.0150	0.0192	0.0672	0.176	0.626	4.08				
S4	0.00417	0.0101	0.0117	0.0332	0.0745	0.212	0.600	4.08			
S3	0	0	0	0	0	0.0955	0.201	0.600	4.08		
S2	0	0	0	0	0	0	0.0849	0.201	0.600	4.08	
S1	0	0	0	0	0	0	0	0.0847	0.201	0.600	4.08

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Table 5. Induced currents due to dump of T1 only.

Coil	Induced Current (A) I_0	ΔI	$\Delta I/I_0$ (%)	t_{peak} (sec)
M1	5,207	140	2.69	60
M2	5,207	30	0.58	40
S7	2,589	771	29.0	80
S6	2,631	100	3.80	60
S5	2,663	20	0.75	60

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Table 6. Induced currents due to simultaneous dump of M1, M2, and M3.

Coil	Induced Current (A) I_0	ΔI	$\Delta I/I_0$ (%)	t_{peak} (sec)
T1	6,431	374	5.82	120
S7	2,589	31	1.2	80

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ed increase in current, ΔI; the percentage increase of operating current that the ΔI represents; and the time at which the peak current occurs after initiation of dump. Any percentage increase of less than 0.5% is not recorded.

Table 3 presents results of dumping two different groupings of solenoid coils. In dumping all solenoids at once, only the transition coil is affected; its induced current represents only about a 7% increase over its normal operating current. Figure 3 is a plot of the current in T1 as a function of time after initiation of the dump of all solenoid coils.

Table 3 also shows the result of simultaneously dumping solenoids S1 through S6. In this case, only solenoid coil S7 is affected, but it shows the relatively large increase (about [illegible]) over normal operating current. This increase is large enough to drive the conductor in coil S7 normal. Figure 4 shows the time behavior of the current in coil S7 after dump initiation.

Table 4 gives the results for simultaneous dump of M1, M2, T1, and S7. Of the four magnets that show an induced current, only solenoid S6 exhibits a significant increase in current (about 20%). As shown in Figure 5, this peak in the current occurs about 140 seconds after initiation of the dump.

Table 5 presents the results of dumping only coil T1. The T1 dump affects quite a large number of coils, but only solenoid S7 shows a significant current increase (about 29%). This is enough to drive the conductor in S7 normal. Figure 6 shows how the current varies with time after dump initiation.

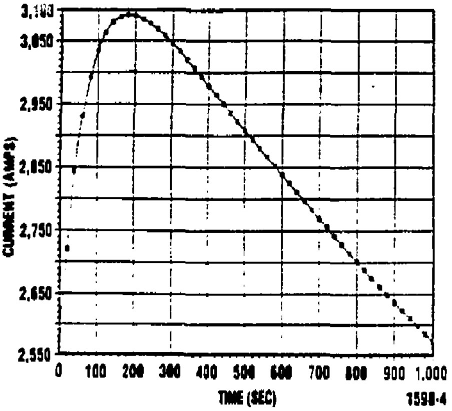

Figure 4. Temporal behavior of current in solenoid S7 after initiation of a dump of solenoids S1 through S6.

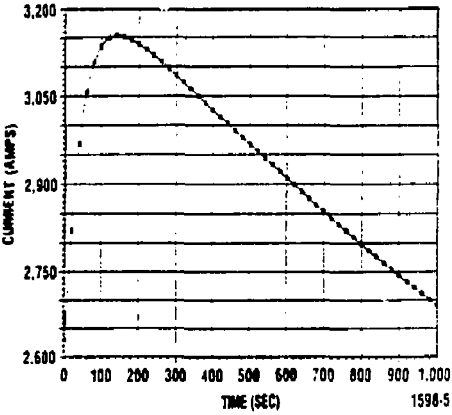

Figure 5. Current in solenoid S6 plotted as a function of time after initiation of a dump of M1, M2, T1, and S7.

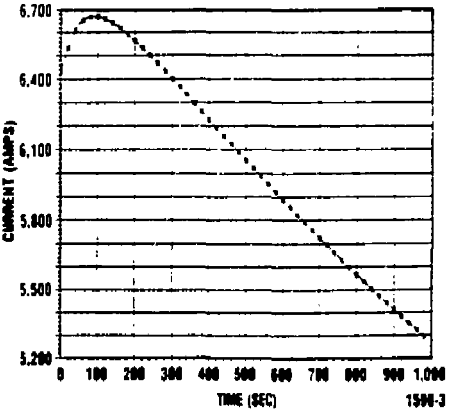

Figure 3. Current behavior in transition coil T1 after initiation of a dump of coils S1 through S7.

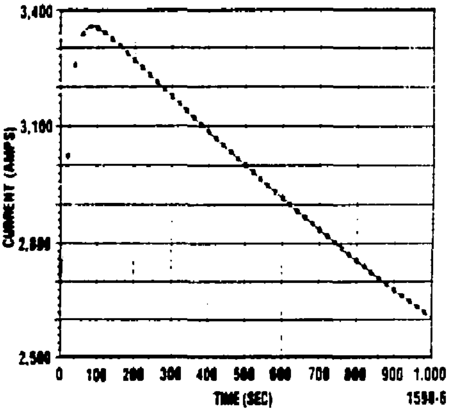

Figure 6. Current behavior in solenoid coil S7 after initiation of a dump of transition coil T1 only.

Simultaneous dump of M1, M2, and M3 is summarized in Table 6. Only transition coil T1 and solenoid S7 are affected. The transition coil suffers the largest current increase, but even that surge amounts to only 6% over normal operating current. Figure 7 illustrates the temporal behavior of the current in T1 after initiation of the dump.

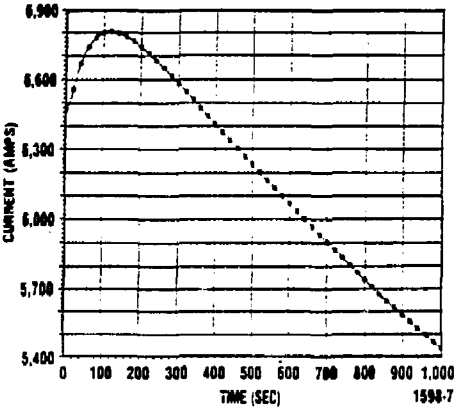

Figure 7. Temporal behavior of current in transition coil T1 after initiation of a dump of M1, M2, and M3

Discussion

Depending upon the magnet group that is dumped, currents induced in the remaining magnets of a closely coupled magnet system can be large. As we have seen, MFTF-B magnet system currents, in some instances, show increases of 20% or 25% over the normal operating current. This large induced current can have two deleterious effects.

First, the induced current may lead to a total current in the coil that exceeds the critical current of the conductor, leading to a quench of the conductor and, consequently, to an emergency dump of the magnet affected. In MFTF-B, exactly this scenario can take place in solenoid S7. Steps to reduce the induced current that can be taken are: (1) increase the number of turns in S7 to lower the operating current, (2) reduce the dump voltage of S7 and the other magnets closely coupled to it, or (3) a combination of these methods.

*The second deleterious consequence of such large induced cur*rents is that electromagnetic loads on the magnet and conductor may become excessive. This could pose a serious threat to either the structural integrity of the magnet or the state of strain of the conductor. Of course, to answer fully the question of whether the electromagnetic loads are too large, one would have to calculate the total magnetic field at the time of peak current.

Another consequence of mutual coupling is that the current decay time constants of the dumped magnets tend to increase. This lengthening of the discharge time results in a small increase in conductor adiabatic temperature rise over the rise to be expected in dumping a solitary magnet. In MFTF-B, the increase is between 3 and 70K depending on the magnet and dump grouping.

We have presented in this paper the results of a computer study of induced currents in the MFTF-B magnet system. This type of investigation should be carried out in any magnet system consisting of coupled magnets to assure the magnet designer that induced currents do not lead to serious structural, thermal, or electrical failure modes.

Acknowledgement

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