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SWITCHING TRANSIENTS IN THE
MFTF YIN YANG COILS

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SWITCHING TRANSIENTS IN THE MFTF YIN-YANG COILS

ABSTRACT

This report is a study of the transients caused by the fast dump of large superconducting coils. Theoretical analysis, computer simulation, and actual measurements are used. Theoretical analysis can only be applied to the simplest of models. In the computer simulations two models are used, one in which the coil is divided into ten segments and another in which a single coil is employed. The circuit breaker that interrupts the current to the power supply, causing a fast dump, is represented by a time and current dependent conductance. Actual measurements are limited to measurements made incidental to the coils' performance tests.

It is found that the breaker opening time is the critical factor in determining the size and shape of the transient. Instantaneous opening of the breaker causes a lightly damped transient with large amplitude voltages to ground. Increasing the opening time causes the transient to become a monopulse of decreasing amplitude. The voltages at the external terminals are determined by the parameters of the external circuit. For fast opening times the frequency depends on the dump resistor inductance, the circuit capacitance, and the amplitude on the coil current. For slower openings the dump resistor inductance and the current determine the amplitude of the voltage to ground at the terminals. Voltages to ground are less in the interior of the coil, where transients related to the parameters of the coil itself are observed.

The studies showed that for the circuit breaker chosen for the MFTF coils, which has an opening time in the millisecond range, the transients are negligibly small.

1. INTRODUCTION

Superconducting magnets are normally designed for dc operation. However, because of the distributed capacitance between different parts of the winding and the winding and ground, the coil is a highly undamped resonant circuit. Even a small disturbance has the potential to excite a large amplitude oscillation with voltages that could damage the insulation.

The largest disturbance experienced by the MFTF magnets is a fast dump. In a fast dump the circuit breakers connecting the magnet to the power supply are opened and the current in the coil is forced through the dump resistor.

Little attention has been paid to the threat of insulation damage from resonant oscillation in superconducting coils. One of the earliest references to the oscillatory behavior of coils with specific reference to superconducting coils is Brechna (1973) who identified and described the behavior. The only reported damage from high frequency, high voltage oscillations was described by Gabriel and Burkhart (1977). They conducted experimental and analytical investigations that showed the unexpected failure of a superconducting coil was due to this source. Recently, Chowdhuri (1981) analyzed the resonances of a superconducting coil and showed the relationship of this behavior to the coil's application as an energy storage coil in a power system.

The transient behavior of large superconducting coils closely parallels the transient behavior of large transformers, on which there is an abundant literature. The analogy is closer than the dissimilarity between the devices might indicate. At high frequencies the transformer is essentially a capacitive-inductive device with the resistance having little effect. Therefore, superconductivity is of little consequence (Abetti, 1953). In addition, an iron core coil can always be converted to an equivalent air core coil (Abetti, 1953).

The main differences between power transformers and superconducting coils are operational ones. The transformer is subjected to surges caused by lightning and other phenomenon. The voltage levels of the surges directly threaten the insulation.

Superconducting magnets, except those connected to power systems, operate in a more protected environment and no high voltage surges are present. The threat comes from rapid switching that excites the resonant modes of the coil.

Since the transient behavior of superconducting coils and power transformers are similar and since there exists a large literature on transformers but a sparse literature on superconducting coils, a brief review of the transformer literature is in order. In 1959 Abetti gave an excellent review and bibliography of what constitutes the main body of the literature. Two supplements followed in 1962 and 1964. Since that time the few publications that have appeared have been largely devoted to methods of computer simulation.

The resonant properties of the transformer and the relationship to insulation failure was recognized early in this century. As early as 1919, Blume and Boyajian analyzed the transformer as a modified transmission line using the standing wave theory. Later work modified this analysis by taking into account the effect of mutual inductance and the winding geometry. Much of this work is summarized in the books by Rudenberg (1968), Heller and Veverka (1968) and Greenwood (1971). With the advent of large computers investigators turned to lumped parameter simulations of the transformer. Here the difficulties are related directly or indirectly to the dimensionality of the model of the transformer and to computing capacity. A fundamental problem is how to reduce the dimensionality and still preserve the behavior of the coil. The simplest and most common approach is to represent the transformer as a chain of series connected inductances with shunt capacitance and capacitance to ground. It has been shown that the number of inductances must be several more than the number of natural frequencies to be preserved (Abetti and Maginiss, 1953). Mutual inductance is also important.

The transformer literature is large, and although relevant to superconducting coils does not deal with the operating conditions peculiar to superconducting coils. The threat to superconducting coils is less severe and comes from switching transients rather than surges from the outside. In general, there is no restrictions on how switching can be carried out. Therefore, it is possible to control the amplitude of the switching transients by controlling the switching process. This is the main topic of this report.

2. LUMPED PARAMETER MODELS OF THE COIL

Introduction

The superconducting coil is a three-dimensional distributed network of capacitance and mutually coupled inductance. In order to simulate its behavior on a digital computer it must be reduced to a lumped network; in order to simulate it conveniently, the network must fit into an available network analysis code. The most suitable code on the MFE computer is Sceptre. The chief limitation of Sceptre in this application is that it will accept only 50 mutual inductances.

A representation of the coil that is amenable to computer analysis consists of a ladder network with series connected mutually coupled inductances, shunt capacitances, and capacitances to ground. A string of ten inductances leads to 40 mutual inductances, consequently a network containing ten inductances is the largest the Sceptre code will accommodate.

The bulk of this chapter describes how the inductances and capacitances of the simplified model are obtained from the three-dimensional geometry of the coil. The genesis of the inductances and capacitances is quite different. In order to calculate the inductances, it's necessary to take into account the geometry of the entire coil. This is a complex calculation that can only be accomplished with the help of the computer. The EFFI code was used.

Calculation of the capacitances is much simpler. In spite of the complexity of the coil's geometry, the dimensions are such that the conductors form long parallel plate capacitors with each other and with the ground plane. The cross-section of the coil suggests a possible equivalent capacitive circuit in which each turn is a node. This circuit can be simplified to one in which each layer is a node. This is an appealing model, but still beyond the capability of the Sceptre code. Therefore, the model is simplified to an eleven node or ten-coil model by combining the layer capacitances. A one-coil model is also developed. When combined with a model of the external circuit, the one-coil model is the most complex model amenable to non-numerical analysis.

The Geometry of the Yin Yang Coil

As Figure 1 shows, the yin-yang pair of superconducting coils have a complex geometry and are close enough that coupling between coils is appreciable. During the short-lived high frequency transient induced by a fast dump, the current in the coils does not change appreciably. Therefore, the mutual inductance between the coils can be neglected and each coil considered separately.

The Capacitances

A cross-section of the coil, which consists of 58 layers with 24 turns per layer, is shown in Figure 2. Within the coil pack the conductors and the insulation that separates them form a separate grid. At the bottom and right side, which are part of the winding form, the insulation to ground is uniform. The top and left sides are welded in place after the coil is wound. At these surfaces, the insulation to ground is much thicker, consisting as it does of filler material.

A start in developing a lumped representation of the capacitances is to consider each turn a node. A network with the same geometric orientation as the coil itself is shown in Figure 3. The six major kinds of capacitive coupling are shown in the diagram.

C_{ga} = The capacitance from a turn on the bottom layer and inside layers to the ground plane.

C_{gb} = The capacitance from a turn on the outside layer to the ground plane.

C_{gc} = The capacitance from a turn on the outside layer to the ground plane.

C_t = The capacitance between a turn and an adjacent turn in the same layer.

C_l = The capacitance between a turn and an adjacent turn in the next layer.

Other capacitances that were considered are: the capacitance between a turn and turns not adjacent and the capacitance between an interior turn and ground. It was decided that because of the increased spacing and shielding offered by the other conductors that these capacitances are negligible.

FIGURE 1-
The Two Yin-Yang MFTF Coils

FIGURE 2.
The cross-section of a coil

FIGURE 3.
Capacitance Network: Each Turn a Node

It was also determined that the capacitance between adjacent turns on the same layer C_t has much less effect than the capacitance between layers C_l . Although the magnitudes of the two capacitances are comparable, the voltage from turn to turn is roughly $1/24$ the voltage between layers. Therefore, the charge stored in the capacitance between turns is about $1/24$ of the charge between layers. The energy stored is even less, $1/24^2$. In view of this fact, the capacitance between adjacent turns on the same layer was neglected.

Since the layers are uniformly wound, the capacitance between layers per unit length is the same throughout the coil. However, the capacitance to ground is different from one location to another. The bottom layer has the greatest capacitance to ground. Individual turns along the inside of the coil also have a large capacitance to ground. Because of the way the coil is constructed, the capacitance from the outside of the coil and the top of the coil to ground is less.

Simplification of the Capacitive Network

A representation in which each turn is a node leads to a lumped parameter model of excessive dimensions. In order to use the Sceptre code, the number of coils must be reduced.

The first step in the simplification is suggested by the observation that the interior turns have little capacitance to ground. The capacitance to ground is concentrated along the top, bottom and sides. There is, in effect, a channel around the perimeter of the coil's cross-section along which the capacitive voltage to ground is transmitted. Figure 4 shows the circuit that this concept implies. In it, all of the layer-to-layer capacitances except those between the peripheral nodes have been neglected. The nodes at each end of a layer remain connected by the series string of turn-to-turn capacitances which have been combined to form a single capacitance C_T .

The twenty-fourth turn of each layer is connected to the first turn above it, allowing Figure 4 to be redrawn as the simplified diagram shown in Figure 5. When the parallel capacitances are combined as in Figure 6, the network forms a simple capacitive ladder, except for the top and bottom layers. In these layers, each turn has significant capacitance to ground and consequently each layer itself forms a ladder network.

FIGURE 4.
Geometry of the Simplified Model

FIGURE 5. The Reduction of the Simplified Model to a Ladder

FIGURE 6.
Simplification of the Ladder

If the fine detail in the bottom and top layers is replaced by additional capacitance to ground, there results a model with 58 nodes that could be called the layer model. This representation is attractive because of the direct relationship between the actual geometry and the model. However, the number of coils and mutual inductances is beyond the capacity of the Sceptre code.

The Ten-Coil Model

In order to match the restrictions of the Sceptre code, the layer model must be simplified to the ten coils circuit shown in Figure 7. The capacitances to ground for the ten-coil model were obtained by summing all of the capacitances to ground in the layer model and then dividing this sum equally among the ten-coil capacitances. The special character of the top and bottom layer is lost, but the result is a uniform model.

The layer-to-layer capacitances are combined by placing them in series between the new nodes, which are $58/10$ layers apart. Therefore, the shunt capacitances of the ten-coil model is $10/58$ of the layer capacitance.

The inductances for the ten-coil model are derived from inductances calculated with the EFFI code. In the original EFFI study the coil was divided into eight equally long sections. Because of the dissimilar geometry of the section, the mutual and self-inductance of each section is different. A uniform ten-coil model is derived from these values by a method described in Appendix A.

The preceding procedures, in particular the reduction of the capacitive layer model to the ten-coil model, have a degree of arbitrariness to them. It would be difficult to rigorously justify all of the steps. It might be argued that the capacitance should be divided in some other way, for example, to preserve the energy stored under a certain voltage distribution. Ideally, the ten-coil model should retain the major features of the actual coil. It's important that the natural frequencies of the reduced model be a subset of the natural frequencies of larger models and the device itself. It's also important, in this case, that the amplitude of the voltages to ground in the model correspond to those in the actual coil. In general, there is no known method of forming a model that is certain to meet these goals.

FIGURE 7. The Ten-Coil Model

The One-Coil Model

Simple though it may be in comparison with the coil itself, the ten-coil model is too complex for analysis. The most complex model that lends itself to analysis, as opposed to numerical experimentation, is a model in which the coil is represented by a single inductance. The shunt capacitance and capacitance to ground are incorporated as shown in Figure 8. When combined with the external circuit, this model exhibits the major features of the transients at the terminals of the coil.

The shunt capacitance in the one-coil model is obtained by combining all the shunt capacitance of the layer model in series. The capacitance to ground is obtained by summing the capacitance to ground of the layer model and dividing it between the two terminals.

The External Circuits

The power supply and dump resistor circuit for one of the MFTF superconducting magnets is shown in Figure 9(a). During normal operation the slow and fast dump circuit breakers are closed. Opening the slow dump breaker places the slow dump resistor in series with the power supply and coil, causing a slow decay. The induced voltages are less than during a fast dump. A fast dump begins when the two circuit breakers open, interrupting the flow of current to the power supply, and forcing the coil current which cannot change instantaneously into the dump resistor. The rapid rise of current in the dump resistor is opposed by the inductance of the resistor and the connecting cables, triggering a transient that excites the coil resonances.

Figure 9(b) shows a circuit model in which the distributed system of cables and devices is replaced by lumped parameters. The power supply can be represented by a simple resistance. However, the cables that connect the power supply, coil, and dump resistor have significant shunt capacitance and capacitance to ground. Equally important is the series inductances, much of which is concentrated in the dump resistor.

The equivalent circuit can be simplified by combining the resistances and concentrating the capacitances at the coil. The resultant circuit is shown in Figure 9(c).

FIGURE B.
The one-coil model

(a) A schematic diagram

(b) The circuit model

FIGURE 9.
The Circuits Connected to the Coil

$$C_{ge} = C_{bg} + C_{dg}$$

$$C_{se} = C_b + C_d$$

(c) A simplified model

FIGURE 9. (continued)
The circuits connected to the coil

Consolidation of the Coil Models And the External Circuit

The external circuits and the models of the coil can be combined to form a single equivalent circuit. Figure 10 shows the process for the one-coil model. Both the external circuit and the coil contain capacitances to ground and shunt capacitances that can be combined.

3. THE CIRCUIT BREAKER

Introduction

The circuit breakers used in a fast dump of the MFTF coils are dc circuit breakers of conventional electromechanical construction. The circuit is broken by a spring driven mechanical contactor. Natural convection due to the heat of the arc and forced air due to action of "puffers" lengthen the arc in a special chute, eventually extinguishing it.

Although the circuit breaker is conventional, the application is not. In a conventional circuit the circuit breaker must interrupt a current that is determined by the source and the impedance of a faulted circuit (Greenwood 1971). In a superconducting magnet application, the current that is interrupted is the current in the coil. This is the maximum current available. Furthermore, while it may be desirable to rapidly interrupt the current to a faulted conventional circuit, there is no such requirement in the superconducting circuit. In fact, as this report shows, it is desirable to interrupt the current slowly.

Although circuit breakers are in wide use and are simple mechanically, their behavior as an electric circuit element is not simple. During interruption of the current a hot plasma is formed that is capable of rapid changes in properties over a wide range (Cobine 1941). The circuit to which the breaker is connected is important in determining the behavior. In addition, since the principle applications are in ac circuits, relatively little attention has been paid to dc circuit breakers. In an ac circuit the arc is usually extinguished at a zero of the current wave while in dc circuits the arc must be extended until the current can no longer be maintained.

(a) The One-Coil Model and the Simplified Model of the External Circuit

(b) The External Circuits and the One-Coil Model Combined

FIGURE 10.
Consolidation of the One-Coil Model and the External Circuits

When a fast dump is initiated by opening the circuit breaker, the current to the power supply is interrupted but the current in the coil remains substantially unchanged. The coil current is diverted to the circuit capacitance and the dump resistor, generating a voltage that depends on the rate of change of current, the inductance of the dump resistor and its cables, and the capacitance. This voltage appears across the circuit breaker, and together with the current determine the energy that must be dissipated in the circuit breaker (Boehne and Jang 1947).

A number of models of the circuit breaker are based on the physics of the arc. The Cassie model and the Mayr model represent the arc as a variable conductance that depends on the arc properties (Smith 1974, Browne 1978). In the Cassie model, the arc conductivity is held constant and the diameter is varied; in the Mayr model the conductivity is variable and the diameter constant.

The Cybernetic Arc Model

The cybernetic arc model (Swanson and Roidt 1971), proposed by Hochrainer and Grutz, considers the arc to be an energy feedback system with energy supplied by the arc and dissipated in the surroundings. Smith (1974) demonstrated that this model has the virtue of being related to observable characteristics of an actual circuit breaker rather than the theory of the arc. Because of this advantage, the cybernetic arc model was chosen for the study described in this report.

In the cybernetic arc model the arc is represented by a variable conductance that is the dependent variable in a first order differential equation. The equation has a time constant that is dependent on the current through the breaker and a forcing or input that also depends on the current.

The differential equation is

$$\frac{dg}{dt} + \frac{g}{\tau(i)} = G(i) \quad (1)$$

where

- t = time
- $i(t)$ = the current through the arc
- $g(t)$ = the conductivity of the arc
- $G(i)$ = the current dependent static conductivity, that is; the conductivity the arc tends toward if the current is constant for a long time
- $\tau(i)$ = the current dependent time constant

The dependency of the time constant τ and the static conductivity G on i can be determined, in principle, from experimental voltage and current records of a circuit interruption. The values for a particular current i_0 can be determined if two sets of time records containing i_0 are available. From the two sets of plots, set 1 and set 2, the instantaneous values of the conductance $g_1(i_0)$ and $g_2(i_0)$ and the instantaneous values of the derivative of the conductance $g_1^1(i_0)$ and $g_2^1(i_0)$ are determined. Then from the above equation

$$\tau(i_0)g_1^1(i_0) - G(i_0) = -g_1(i_0)$$

$$\tau(i_0)g_2^1(i_0) - G(i_0) = -g_2(i_0)$$

The unknowns $\tau(i_0)$ and $G(i_0)$ are obtained by solving these two simultaneous equations. If this is done for a number of values of i_0 the relationship between the breaker's current and the two current dependent parameters is established.

As Smith found in his 1974 dissertation, the experimental determination of the parameters is not as easy as it sounds. Considerable effort is necessary to obtain a model that matches the circuit breakers behavior. The technology demonstration tests of the magnets did not yield enough information to satisfactorily derive the parameters as described. One problem was the paucity of trials but another was the noisiness of the time records. Noise makes it difficult to determine the instantaneous values. The possibility of additional tests with a short circuit replacing the coil was considered. However, it is not clear that the model of the circuit breaker is the same for different circuit conditions (Smith, p.34).

The difficulty in deriving the parameters from time records does not invalidate the usefulness of the cybernetic arc model. It remains a realistic model of breaker behavior. Numerical experimentation showed that by selecting suitable relationships between the time constant and the static conductivity and the current the behavior of the breaker could be modified in a predictable manner.

Selection of the Parameters for the Circuit Breaker Model

The dependence of the static conductivity $G(i)$ and the time constant $\tau(i)$ on the breaker current i was found by trial and error. A rough estimate of the conductance and time scale was made from test records of the breakers voltage and current. After a few trials it was possible to match the computer simulations to the tests.

There are no constraints on the relationship between the time constant and the current. However, the choice of $G(i)$ is constrained by the circuit. Only a certain amount of current, the coil current, is available at any time. The conductance of the breaker can't be more than the conductance that would pass this current.

An upper limit to the value of $G(i)$ is calculated using the static circuit shown in Figure 11 in which inductance and capacitance are neglected. The steps are as follows. A value of voltage across the circuit is chosen. The total conductance $G_d + G_b$ is $\frac{I}{V}$, where I is the coil current. This current remains virtually constant during operation of the circuit breaker. The maximum allowable G_b is obtained by subtracting G_d from $G_b + G_d$ and I_b is calculated. The simulation of the circuit breaker performs satisfactorily if G_b is chosen sufficiently far below the maximum value. If larger values are chosen an equilibrium point is reached in which the breaker conductance remains fixed for a long time.

The functional relationship between the static conductance and the time constant and the current can be expressed either as an equation or as a table. Tables were used in the simulations. Appendix D describes the Sceptre simulation.

g_b = Breaker Conductance

$$g_d = \frac{1}{R_d}$$

FIGURE 11.
The dc or Static Circuit of the Coil,
Breaker, and Dump Resistor

4. ANALYSIS OF THE ONE-COIL MODEL

Introduction

The one-coil model combined with the external circuit is the most complex model that can be analyzed without recourse to numerical methods. This model cannot show the behavior within the coil, such as internal oscillations. However, it does exhibit the principle modes of external behavior and leads to an understanding of the factors affecting the critical voltages.

Simplification of the Model

For the purposes of analysis the one-coil model can be simplified further. The center-taped resistor gives the circuit a partial symmetry with respect to ground. Dividing the breaker branch and the shunt capacitance into two parts completes the symmetry, allowing the circuit to be simplified as shown in Figure 12.

Instantaneous Opening of the Breaker

Simple though the circuit is, it is not possible to analytically determine its behavior using a model of the circuit breaker in which the breaker is represented by a variable resistance. However, the circuit can be analyzed if the breaker opens instantaneously. Although not realistic, this analysis provides an initial understanding of the circuit and a benchmark with which to compare other models.

Instantaneous opening of the breaker implies the removal of the R_b, L_b branch of the circuit. The remaining circuit consists of the superconducting coil, the capacitance, and the dump resistor and its associated inductance. The characteristic equation of this circuit is

$$\frac{S^3 + R_d}{L_d} S^2 + \frac{L_c + L_d}{C_e L_c L_d} S + \frac{R_d}{C_e L_c L_d} = 0$$

(a) The original one-coil model

(b) The simplified model

Figure 12.
Simplification of the one-coil model

One of the natural frequencies of this circuit is a slowly decaying exponential due to the decay of the coil current. The other is a high frequency oscillation due to the interaction of the shunt capacitance and the series inductance of the dump resistor.

For all practical purposes, the decay of coil current is so slow that the current in the coil can be considered constant during the opening of the circuit breaker. Therefore, the analysis can be simplified by replacing the coil with a constant current source as shown in Figure 13. The characteristic equation of this circuit is

$$s^2 + \frac{R_d}{L_d} s + \frac{1}{C_e L_d} = 0$$

Comparing this with the standard equation

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$$

yields

$$\text{the undamped natural frequency} = \omega_n = \frac{1}{\sqrt{C_e L_d}}$$

$$\text{the damping ratio} = \zeta = \frac{R_d}{2} \sqrt{\frac{C_e}{L_d}}$$

The MFTF coils are very lightly damped, with a damping ratio of .0032. For cases such as these, a simplified calculation of the peak voltage to ground can be made. At zero time, when the breaker opens instantaneously, all of the current from the superconducting coil flows into the capacitance, causing the voltage to rise. For lightly damped circuits the subsequent waveshape is virtually sinusoidal for a number of cycles, as shown in Figure 13(b). The peak voltage can be calculated as follows:

$$\begin{aligned} V_m &= \frac{1}{C_e} \int_0^{T/4} i_c dt = \frac{1}{C_e} \int_0^{\pi/2} I \cos \omega_n t dt \\ &= I \sqrt{\frac{L_d}{C_e}} \end{aligned}$$

FIGURE 13(a).

A Model Representing the Circuit for a Short Time After
Instantaneous Opening of the Breaker

FIGURE 13(b).

The Current Through and the Voltage Across the Capacitance

This is an important result, for it gives a measure of the peak voltage to ground. The peak voltage is increased by increasing the inductance of the dump resistor and its associated cables and decreased by increasing the equivalent capacitance to ground. This capacitance consists of a combination of the cable and coil capacitance to ground and the shunt capacitances.

The Circuit Breaker Represented as a Resistance

In realistic models of the circuit breaker, the breaker is represented by a current or time dependent resistor. Circuits with these models can be solved only by numerical methods. However, some insight into the circuit behavior can be obtained by assuming the circuit breaker resistance is constant and analyzing the resultant circuit.

The one-coil model with the circuit breaker replaced by a constant resistance is shown in Figure 14. The coil has been replaced by a constant current source. The characteristic equation of this circuit is

$$s^2 + s \left(\frac{1}{C_e R_b} + \frac{R_d}{L_d} \right) + \frac{1}{L_d C_e} \left(\frac{R_d}{R_b} + 1 \right) = 0$$

$$\omega_n = \sqrt{\frac{1}{L_d C_e} \left(\frac{R_d}{R_b} + 1 \right)}$$

$$\zeta = \frac{\frac{1}{C_e R_b} + \frac{R_d}{L_d}}{2\omega_n}$$

The effect of the breaker is to shunt the oscillatory RLC circuit, damping the oscillations. As the above equation shows, the damping ratio increases as R_b decreases; approaching infinity as R_b approaches zero.

FIGURE 14.
A Model in Which the Circuit Breaker is Considered
to be a Constant Resistance

The effect of R_b on the voltage to ground is even more important. At the initial instant all of the current from the superconducting coil flows into the capacitance C_e . As the voltage across C_e rises some of the current flows through R_b and some through the dump resistor branch. However, at no time can a current larger than the coil current flow through R_b . Therefore, the voltage across R_b , which is also the voltage from a terminal to ground, can never be more than IR_b .

The voltages to ground for different values of R_b can be compared with the voltages that occur when the breaker opens instantaneously. In the previous section it was found that for the MFTF coils operating at 6000 A the peak voltage to ground when the breaker opens instantaneously is 40,430 V. A similar value results when R_b is 10^6 . However, when R_b is 3 ohms the peak is only 8,100 V and when it is .001 ohms the peak is about 5 V. These values were obtained from computer simulations.

The effect of the breaker on the oscillations can now be described in qualitative terms. As the breaker begins to open it forms a low resistance path, shunting the oscillatory circuit. If the breaker remains in the low resistance regime for a sufficient time the oscillations are damped out and the energy initially transferred from the superconducting coil to the capacitance is dissipated. If the breaker passes to a high resistance regime rapidly, oscillations persist.

5. COMPUTER SIMULATIONS OF THE ONE-COIL MODEL

Introduction

The one-coil model, combined with the external circuits is shown in Figure 10(b). Simulations, using the Sceptre code, were made to determine the effect of breaker opening time, circuit capacitance, dump resistor inductance, and breaker inductance.

The base values used in these simulations are shown in Appendix B. Other values used are expressed as multiples of these values.

Simulations were made for instantaneous opening of the breaker and for slower openings. In order to open the breaker instantaneously, the breaker resistance is changed from zero to a very large value in zero time. For slower openings the cybernetic arc model is used. The breaker opening times are approximately 6×10^{-6} , 6×10^{-5} , 6×10^{-4} and 3×10^{-3} seconds. The relationship between the breaker current I_b and the static conductivity G_b and time constant of the breaker equations, which is expressed in tabular form, is shown in Appendix B. Samples of the Sceptre programs are given in Appendix D.

The Effect of the Breaker Opening Duration

The breaker speed was found to be the most important factor in determining the size and shape of the transient voltages. Increasing the time of interruption, in effect, damped out the oscillations and decreased the peak voltages. The results of the simulations are shown in Table 1.

Instantaneous opening of the breaker, the only case amenable to analysis, serves as a benchmark with which the other responses can be compared. For the values used, the transient is a near perfect sinusoid, with a peak voltage to ground of over 40,000 volts. Calculated and simulated results agree closely.

A cybernetic arc model in which the arc is interrupted in approximately 6×10^{-6} s gives results that are similar to instantaneous opening. Increasing the interruption time

changes the response markedly. The sinusoidal transient degenerates into a single pulse and the peak voltage to ground is reduced. Increasing the interruption time to 6×10^{-5} , an increase of one order of magnitude, decreases the peak voltage to ground to 3,760, about one order of magnitude.

Figures 15 through 23 show the time records of the breaker current and the circuit voltages for the simulations listed in Table I. Figure 15 shows the voltage to ground. The remainder of the voltage plots are of the coil voltage, which is exactly twice the voltage to ground.

The Effect of the C , L_b and L_d

A study was made of the effect of the circuit capacitance, inductance of the dump resistor L_d , and the inductance of the breaker circuit L_b on the waveshape and amplitude

TABLE I. The Effect of Breaker Opening Time on the Transient Voltage to Ground, Using the One-Coil Model

Breaker Opening Time (seconds)	Nature of the Response	Maximum Voltage to Ground (Volts)		Frequency (Hz)	
		Simulation	$I \sqrt{\frac{L_d}{C_e}}$	Simulation	$\frac{1}{2\pi \sqrt{L_d C_e}}$
Instantaneous	Almost sinusoidal	40,500	40,400	134,000	134,000
6×10^{-6}	Almost sinusoidal	19,950	--	136,000	--
6×10^{-5}	Single pulse	1,880	--	--	--
6×10^{-4}	Single pulse	340	--	--	--
3.5×10^{-3}	Overdamped	255*	--	--	--

Initial coil current = $I = 6000$ A.

*The maximum voltage to ground is the product of the current and dump resistor resistance, which is 255 V.

FIGURE 15

The voltage to ground for the one-coil model, instantaneous interruption time

FIGURE 16.
The breaker current for the one-coil model, interruption time
approximately 6×10^{-6} s

FIGURE 17.

The voltage across the coil for the one-coil model, interruption time
approximately 6×10^{-6} s

FIGURE 18.

The breaker current for the one-coil model, interruption time
approximately 6×10^{-5} s

FIGURE 19.

The voltage across the coil for the one-coil model, interruption time
approximately 6×10^{-5} s

FIGURE 20.

The breaker current for the one-coil model, interruption time
approximately 6×10^{-4} s

FIGURE 21.

The voltage across the coil for the one-coil model, interruption time
approximately 6×10^{-4} s

FIGURE 22.
The breaker current for the one-coil model, interruption time
approximately 3.5×10^{-3} s

FIGURE 23.

The voltage across the coil for the one-coil model, interruption time
approximately 3.5×10^{-3} s

of the transient. The waveshape was not affected over the range of parameter values studied. Only the dump resistor inductance appreciably affected the peak amplitude of the voltage to ground.

The results of the study are summarized in the two part listing in Table 2. The first part is for the cybernetic arc model giving a breaker opening time of 6×10^{-5} s and the second is for the model with a 6×10^{-6} s opening time. The first line in each part is for the simulation described in the previous section. The listings, C , L_d and L_b denote the values given in Appendix B.

Simulations were made with the values of L_d and C halved and doubled; L_b was changed over a wider range. The waveforms remained essentially the same; the slowly opening breaker produced a monopulse transient and the fast opening breaker a near sinusoid. The dump resistor inductance L_d was the only parameter that appreciably affected the peak voltage to ground. Increasing the value of L_d proportionately increased the value of the peak voltage for both breaker speeds. Figure 24 shows the effect of L_d on the monopulse transient produced when the breaker opens in 5×10^{-5} s. The amplitude of the oscillation produced by the more rapid breaker opening is affected in a similar manner. Changing L_d also affects the frequency of these near sinusoidal oscillations.

Changing the circuit capacitance over a range of eight to one did not have a noticeable effect on the peak voltage to ground for both breaker speeds. The effect on the peak voltage of changing L_b over a wider range was also negligible.

The results of the simulations are only partially explainable in terms of the two simple models studied, the model in which the breaker opens instantaneously, and the model in which it is replaced by a constant resistor. When the breaker opens instantaneously the peak amplitude is $I \sqrt{\frac{L_d}{C_e}}$. When the breaker is replaced by a fixed resistor the relationship is more complicated, but the peak amplitude still depends on both L_d and C_e . However, in the simulations using the cybernetic arc model of the breaker only L_d affects the peak voltage. No simple explanation has been found for this behavior.

The simple models are somewhat more successful in predicting the frequency of oscillation that results when the breaker opens rapidly. Although changing the circuit capacitance does not affect the amplitude of the oscillation it does affect the frequency.

TABLE 2. The Effect of Dump Resistor Inductance, Circuit Capacitance, and Breaker Inductance on the Transient Voltage to Ground, Using the One-Coil Model

For a Breaker Opening Time of Approximately 6×10^{-5} s				
Capacitance	Dump Inductance	Breaker Inductance	Maximum amplitude of voltage to ground (volts), a single pulse	
C	L_d	L_b	1880	
C	1.5 L_d	L_b	1010	
C	2 L_d	L_b	3015	
.5 C	L_d	L_b	1865	
2 C	L_d	L_b	1880	
C	L_d	1.18 L_b	1880	
C	L_d	3 L_b	1895	

For a Breaker Opening Time of Approximately 6×10^{-6} s						
Capacitance	Dump Inductance	Breaker Inductance	Maximum amplitude of voltage to ground (volts), a near sinusoid	Frequency (Hz)		
				Simulation	$\frac{1}{2\pi\sqrt{L_d C_e}}$	
C	L_d	L_b	19,950	136,000	134,000	
C	.5 L_d	L_b	10,650	192,000	119,000	
C	2 L_d	L_b	35,550	95,200	94,800	
.5 C	L_d	L_b	19,900	192,000	119,000	
2 C	L_d	L_b	18,750	95,200	94,800

FIGURE 24.

The Effect of L_d on the Voltage to Ground
for the Circuit Breaker Opening in Approximately 6×10^{-5} s

6. COMPUTER SIMULATIONS OF THE TEN-COIL MODEL

Introduction

Simulations, using the Sceptre code, were made of the ten-coil model shown in Figure 7 with the addition of the external circuits as depicted in Figure 9(c). The values are given in Appendix C. A sample Sceptre program is shown in Appendix D.

Instantaneous Opening of the Breaker

Instantaneous opening of the breaker, which causes the largest peak voltages to be generated, serves as a benchmark for comparison with slower breaker behavior. The voltages to ground from the nodes on the left side of the ten-coil model are shown in Figures 25 to 30. The remaining nodes, on the right side, have similar voltages because of the symmetry of the model.

The voltage between the outside terminal and ground, V_{c1} , is an almost pure sinusoid with an amplitude much greater than any of the interior voltages. At the node next to the terminal the voltage, V_{c2} is only a tenth the size. The value decreases rapidly as the center of the coil is approached. The mid-center voltage, V_{c6} , should be zero because of the symmetry of the circuit, but, instead, imperfections in the numerical simulation cause it to be a small value.

The sinusoidal waveshape of the voltage at the terminal is also present in the interior voltage but other lower frequencies also make their appearance. Since the system is a higher order one, a large number of natural frequencies exist. However, only a few have a large enough amplitude to be visible, and only one, the nearly sinusoidal signal at the terminal appreciably affects the voltage to ground.

The voltage at the terminal is related in a simple way to the external circuit parameters and can, as a result, be predicted using the one-coil model. The ten-coil model is reduced to an equivalent one-coil model by substituting a single coil for the ten coils, forming an equivalent shunt capacitance, and combining the capacitance at the

FIGURE 25.

The voltage from the outside node, node 1, to ground for the ten-coil model,
instantaneous opening of the breaker

FIGURE 26.

The voltage from the first inside node, node 2, to ground for the ten-coil model,
instantaneous opening of the breaker

FIGURE 27.

The voltage from the second inside node, node 3, to ground for the ten-coil model,
Instantaneous opening of the breaker

FIGURE 28.

The voltage from the third inside node, node 4, to ground for the ten-coil model,
instantaneous opening of the breaker

FIGURE 29.

The voltage from the fourth inside node, node 5, to ground for the ten-coil model,
instantaneous opening of the breaker

FIGURE 30.

The voltage from the center inside node, node 6, to ground for the ten-coil model,
instantaneous opening of the breaker

terminal with the external capacitance, as shown in Figure 10. If this is done for the values used in the simulation, the peak voltage calculated from $I \sqrt{\frac{L_d}{C_e}}$ is 66,870 V and the frequency calculated from $\frac{1}{2\sqrt{L_d C_e}}$ is 221,700 Hz. The values obtained from the ten coil simulation are 66,870 V and 222,200 Hz.

Slower Opening of the Breaker

Simulations were made of the ten-coil model using the same models of the circuit breaker as used for the one coil simulations. The voltages to ground for the exterior node and the first three interior nodes for a breaker opening time of approximately 6×10^{-5} s are shown in Figures 31 to 34.

The results follow the same pattern as exhibited for instantaneous opening of the breaker. The maximum voltage is at the exterior node. The interior voltages steadily decrease as the center node is approached. In addition, frequencies not visible at the exterior node become evident.

The most striking result is the similarity between the size and shape of the voltage at the exterior nodes and the voltages in the one coil simulation. For example, for a breaker opening of 6×10^{-5} s the maximum of the exterior voltage of the ten-coil model is 1877 V, for the one-coil it is 1880, and the two waveforms are indistinguishable. This similarity is a reflection of the fact that it is the external circuit parameters that determine the maximum voltage to ground. In this case the similarity is all the more remarkable because the shunt and ground capacitances of the one- and ten-coil models are different. However, numerical experiments on the one-coil model showed that the capacitance has little effect on the peak voltage when the breaker opens slowly. The inductance of the dump resistor is the predominant influence. In the simulations the one- and ten-coil models have the same dump resistor inductance.

FIGURE 31

The voltage from the outside node, node 1, to ground for the ten-coil model,
 breaker opening time approximately 6×10^{-5}

FIGURE 32

The voltage from the first inside node, node 2, to ground for the ten-coil model,
breaker opening time approximately 6×10^{-5} S

FIGURE 33

The voltage from the second inside node, node 3, to ground for the ten-coil model,
breaker opening time approximately $6 \times 10^5 S$

FIGURE 34

The voltage from the third inside node, node 4, to ground for the ten-coil model,
 breaker opening time approximately 6×10^{-5} s

7. MEASUREMENTS ON THE COILS

Because of economic and technical factors, it is not possible to make measurements over the range of parameters encompassed by the computer simulations. However, an opportunity to record the transients during a fast dump was available during the Technical Demonstration of the MFTF coils. During these performance tests the coil was fast dumped a number of times at currents up to the rated current of 5775 A.

A multichannel wideband magnetic tape recorder and digital transient recorder were employed to record the transient during a fast dump. The bandwidth of the instruments were adequate to record the transients predicted by this study. Records were made of the voltages across the two coils, the voltages to ground, and the current through the circuit breaker. The record for the test at 5775 A is shown in Figure 35. It was produced by recording on the tape recorder at highest speed and playing back at a lower speed. As the records show, the opening of the breaker, which takes place in about three milliseconds, produces a transient with no overshoot.

Figure 35.
Transients recorded during a fast dump from 5775A

8. SUMMARY AND CONCLUSIONS

The study of transients in large superconducting coils is similar to the study of transients in power transformers. However, unless the coil is connected to external lines, it is safe from the large transients that threaten the insulation of power transformers. The main danger is from transients triggered by a fast dump. The objective of this study is to determine the shape and amplitude of these transients and the factors that affect these two attributes.

Three methods were used in this study: theoretical analysis, simulation and numerical experimentation, and measurements taken during the test of the coils. The phenomena can be studied theoretically only by using greatly simplified models. Simulations, while not as limited, are constrained in complexity by the available codes and computers. Actual measurement, because of technical and economic considerations, were limited to incidental measurements made during performance tests of the coils.

The computer simulations use two models, one in which the superconducting coil is represented by ten mutually coupled segments and another in which the coil is represented by a single coil. The model of the coil is combined with a circuit model that takes into account the resistance, capacitance, and inductance of the external circuit. The circuit breaker is represented by a variable conductance that is the dependent variable of a first order differential equation with time as the independent variable. The equation has a current dependent time constant and static conductivity, making the circuit breaker model highly nonlinear.

The two most important factors affecting the size of the voltage to ground are the breaker opening time and the inductance of the dump resistor and its associated cables.

The largest amplitude transient occurs when the current to the power supply is interrupted instantaneously. The current in the coil, which remains unchanged, cannot immediately flow into the dump resistor because of its series inductance. Instead, it initially flows into the system capacitance causing a lightly damped sinusoidal transient

with a frequency depending on the system capacitance and dump resistor inductance. The peak voltage to ground for the one-coil model is proportional to the coil current and the square root of the dump resistor inductance and inversely proportional to the square root of the effective shunt capacitance. If the coil inductance is much larger than the dump resistor inductance, the coil inductance itself has little effect on the frequency or the size of the transient.

Breaker opening times slower than instantaneous can be studied only by computer simulation for even the simplest of coil models. When the breaker opens rapidly, in the order of 6×10^{-6} s, the transients are similar to those that occur when the opening is instantaneous. Increasing the opening time by an order of magnitude causes the shape of the transient to change from a sinusoid to a monopulse. As the breaker opening time decreases so does the size of the transient. For opening times in the millisecond range the transient has no peak; the voltage proceeds smoothly to a voltage equal to the product of the coil current and the dump resistor.

The breaker actually used has an opening time of about three milliseconds. Measurements of the transient showed no peaking, confirming at least for this one point, the validity of the computer studies.

At the slower breaker speeds the amplitude of the monopulse transient is roughly proportional to the inductance of the dump resistor. The circuit capacitance, which is important when the breaker opening is instantaneous, has little effect over this range. Inductance in series with the breaker is also of negligible importance.

Simulations using the ten-coil model show that the maximum voltage to ground occurs at the external terminals of the coil. Due to the way the dump resistor is grounded and the symmetry of the circuit, the center of the coil is at ground. Points on the coil between the center and the ends have intermediate voltages.

At the external terminals the waveshapes and peak voltages obtained from simulations using the ten-coil model are similar to those of the one-coil model. Therefore, the one-coil model can be used to predict the maximum voltage to ground.

The ten-coil model demonstrates the existence of what are an infinite number of natural frequencies in the actual coil. These frequencies, which are lower than the frequency that dominates the response at the external terminals, are visible in the interior voltage.

No attempt was made to estimate the turn-to-turn and layer-to-layer voltage. The ten-coil model is only of questionable utility in this task. A reliable estimate would require a much more complex model.

In final conclusion, theory, computer simulation and measurements have demonstrated that the transients induced in the MFTF coil are small. The main reason for this is the long opening time of the breaker relative to the frequency of the predominant transients. During opening of the breaker the energy which would otherwise be stored in the circuit capacitance is dissipated in the breaker.

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APPENDIX A

A LUMPED PARAMETER MODEL OF THE COIL

The Capacitance, Each Turn a Node

In this model of the coil each turn is considered to be a node, as described in Section 1. The result is the 24 by 58 grid of nodes shown in Figure 3. In this Appendix the capacitance to ground, between layers, and from turn to turn are calculated.

The cross-section of the coil is shown in Figure 2. The jacket forms the ground plane. An equal thickness of Kapton separates the jacket from the conductor on the bottom and right sides. The top and left sides have a greater separation. The relevant dimensions are:

Mean length of coil	18.3 m
Cross-section of conductor	1.24 x 1.24 cm
Insulation between turns	.1143 cm
Insulation between layers	.159 cm
Insulation to ground	
bottom and right side	.540 cm
left side	2.261 cm
top (outside diameter)	7.620 cm
Dielectric constant of G-10,	5.2

The capacitances are calculated from the parallel plate formula

$$C = \frac{8.85 \times 10^{-12} A \epsilon}{d} \quad F$$

where A = area in m^2

d = distance in m.

The turn-to-turn, layer-to-layer, and part of the insulation to the case is not solid, but instead consists of buttons with channels for the liquid helium. The effective dielectric constant of this composite was estimated as 3.0. The following values were calculated. The capacitances are defined in Figure 3.

$$\begin{aligned}C_{ga} &= 2.008 \times 10^{-9} \text{ F} \\C_{gb} &= 0.1423 \times 10^{-9} \text{ F} \\C_{gc} &= 0.480 \times 10^{-9} \text{ F} \\C_l &= 3.203 \times 10^{-9} \text{ F} \\C_t &= 5.271 \times 10^{-9} \text{ F}\end{aligned}$$

The Capacitance, Each Layer a Node

Using the nomenclature defined in Figures 3 through 6, the following values were calculated:

$$\begin{aligned}C_T &= \frac{C_t}{24} = 0.439 \times 10^{-9} \text{ F} \\C_{lp} &= C_T \text{ in parallel with } 2 C_l \\&= 8.035 \times 10^{-9} \\C_{gp} &= C_{ga} \text{ in parallel with } C_{gc} \\&= 2.488 \times 10^{-9}\end{aligned}$$

The Capacitances for the Ten-Coil Model

The capacitances for the ten-coil model are defined in Figure 7.

The capacitance to ground C_{go} is obtained by adding all of the capacitances to ground in the layer model and dividing these uniformly among the eleven-coil capacitances to ground in the ten-coil model. The effect of the top and bottom layers are ignored.

$$C_{go} = \frac{56 \times C_{gp} + 2C_{ga} + C_{gc} + C_{gb}}{11} = 13.087 \times 10^{-9} \text{ F}$$

The series capacitance of the ten-coil model C_{so} is obtained by taking a series combination of the layer model capacitance C_{lp} . There are 5.8 layers in each coil of the ten-coil model. Therefore

$$C_{so} = \frac{C_{lp}}{5.8} = 1.385 \times 10^{-9} \text{ F}$$

The Capacitances for the One-Coil Model

The method used to derive the capacitances of the one-coil mode, which is shown in Figure 8, is similar to that used for the ten-coil model. The capacitance to ground C_{gl} is the sum of the layer model capacitances to ground divided by two

$$C_{gl} = \frac{56 \times C_{gp} + 2C_{ga} + C_{gc} + C_{gb}}{2} = 72.0 \times 10^{-9} \text{ F}$$

The series capacitance C is obtained by taking a series combination of the layer model capacitance C_{lp} along the entire length of the layer model

$$C_{sl} = \frac{C_{lp}}{5.8} = .138 \times 10^{-9}$$

Measured Capacitance to Ground

The measured capacitance to ground for both coils was 80 and 82 $\times 10^{-9}$ F resulting in an average C_{gl} of 41 $\times 10^{-9}$ F. The dominant capacitance to ground was found to be the voltage tap instrumentation external to the magnet. C_{gl} measured with the instrumentation connected was 144 and 203 $\times 10^{-9}$ F for the two coils. The difference was because of cable length.

The Inductances

The mutual and self-inductances for the 10-coil model are based on calculations made by the EFFI code. In these calculations the yin-yang coil was divided into eight, not ten parts. The calculated values are shown in the following table. The self-inductances are along the diagonal, the mutual inductances are off the diagonal.

THE EIGHT-COIL MODEL

Inductances and Mutual Inductances in Henrys

$$M_{ij} = M_{ji}$$

	1	2	3	4	5	6	7	8
1	.243	.207	.165	.136	.114	.097	.084	.073
2		.253	.215	.171	.141	.119	.101	.087
3			.262	.222	.177	.146	.123	.105
4				.271	.230	.184	.151	.127
5					.280	.238	.190	.156
6						.289	.246	.196
7							.299	.253
8								.308

The coefficient coupling of between the eight coils serve as a means of generating a ten-coil model or a model of any other size. The coefficient of coupling k is

$$k = \frac{M_{ij}}{\sqrt{L_i L_j}}$$

The coefficients of coupling for the eight-coil model vary between 1.0 for a coil and itself to .27 between the first and the eighth coil. To derive a ten-coil model with symmetric mutual inductances it is assumed that the coefficient of coupling changes linearly along the coil. Extrapolating the coefficient from the eighth coil to the tenth coil yields .22. The difference in the coefficient from one coil to the next is .078. The following coefficients were then calculated:

Coefficient	Distance between coils	Coefficient of coupling
k_{11}	0 coil	1.00
k_{12}	1 coil	.922
k_{13}	2 coils	.844
k_{14}	3 coils	.766
k_{15}	4 coils	.688
k_{16}	5 coils	.610
k_{17}	6 coils	.532
k_{18}	7 coils	.454
k_{19}	8 coils	.376
k_{110}	9 coils	.298

In the symmetric ten-coil model each of the ten coils contributes the same inductance. Therefore

$$k_{ij} = \frac{M_{ij}}{L_{10}}$$

L_{10} = the self-inductance of each of the coils in the ten-coil model

The total inductive contribution of each coil is the sum of itself and mutual inductances. In addition, the ten-coil model must have the same total inductance as the superconducting coil. Therefore

$$\begin{aligned}
 L &= 10 (L_{10} + M_{12} + M_{13} + M_{14} + M_{15} + M_{16} + M_{17} + M_{18} + M_{19} + M_{110}) \\
 &= 10 L_{10} (1 + k_{12} + k_{13} + k_{14} + k_{15} + k_{16} + k_{17} + k_{18} + k_{19} + k_{110}) \\
 &= 10 L_{10} (1 + .922 + .844 + .766 + .688 + .610 + .532 + .454 + .376 + .298)
 \end{aligned}$$

Since $L = 11.113 \text{ H}$

$$L_{10} = .17123 \text{ H}$$

Using this value of self-inductance for each of the coils in the ten-coil model and the coupling coefficients, the values of mutual inductance were calculated.

THE TEN-COIL MODEL
Mutual and Self-Inductances in Henrys

$$M_{ij} = M_{ji}$$

	1	2	3	4	5	6	7	8	9	10
1	.1712									
2	.1579	.1712								
3	.1445	.1579	.1712							
4	.1312	.1445	.1579	.1712						
5	.1178	.1312	.1445	.1579	.1712					
6	.1045	.1178	.1312	.1445	.1579	.1712				
7	.0912	.1045	.1178	.1312	.1445	.1579	.1712			
8	.0777	.0912	.1045	.1178	.1312	.1445	.1579	.1712		
9	.0644	.0777	.0912	.1045	.1178	.1312	.1445	.1579	.1712	
10	.0511	.0644	.0777	.0912	.1045	.1178	.1312	.1445	.1579	.1712

The External Circuits

The equivalent circuit of the equipment connected to the coil is shown in Figure 9(b). the parameters are defined as follows:

C_b = the shunt capacitance of the cables between the power supply and the coil

C_d = the shunt capacitance of the dump resistor and the cables connecting the coil to the dump resistor

C_{bg} = half the capacitance to ground of the cables connecting the power supply and the coil

C_{dg} = half the capacitance to ground of the dump resistor and the cables connecting it to the coil

L_{bl} = half the inductance of the cables connecting the power supply to the coil

L_{dl} = half the inductance of the dump resistor and the cables connecting it to the coil

R_{bl} = half the resistance of the cables connecting the power supply to the coil

R_{dl} = half the resistance of the dump resistor and the cables connecting it to the coil

The following table shows the values of the quantities for the two yin-yang coils. The average values were used in the simulations.

The Parameters of the External Circuit

	Coil 1	Coil 2	Average
C_b	10.1×10^{-9}	17.1×10^{-9}	13.6×10^{-9}
C_d	7.8×10^{-9}	4.0×10^{-9}	5.9×10^{-9}
C_{bg}^*	3.1×10^{-9}	5.7×10^{-9}	4.4×10^{-9}
C_{dg}^*	10.9×10^{-9}	5.2×10^{-9}	8.0×10^{-9}
L_b^*	2.5×10^{-6}	3.0×10^{-6}	2.7×10^{-6}
L_d^*	8.5×10^{-6}	7.5×10^{-6}	8.0×10^{-6}
R_{dl}^{**}	.0425	.0425	.0425

All values are in farads, henrys, and ohms.

*These values were measured, the other values are calculated.

**This is the value of the dump resistor for a 120 s time constant and is twice the actual value used in the tests.

Figure 9(c) shows the simplified model of the external circuits, one in which the capacitances have been combined as follows:

$$C_{ge} = C_{bg} + C_{dg} = 12.4 \times 10^{-9}$$

$$C_{se} = C_b + C_d = 19.5 \times 10^{-9}$$

Consolidation of the External Circuits And the One-Coil Model

Figure 10 shows the consolidation of the one-coil model and the external circuit. The consolidated capacitance values C_g and C_s are

$$C_g = C_{ge} + C_{gl} = 12.4 \times 10^{-9} + 72.0 \times 10^{-9} = 84.4 \times 10^{-9} \text{ F}$$

$$C_s = C_{se} + C_{sl} = 19.5 \times 10^{-9} + .138 \times 10^{-9} = 19.6 \times 10^{-9} \text{ F}$$

Although the remaining parameter values have been obtained earlier they are listed below for easy reference:

$$L = 11.113 \text{ H}$$

$$L_b = 2.7 \times 10^{-6} \text{ H}$$

$$L_d = 8.0 \times 10^{-6} \text{ H}$$

$$R_d = .0425 \Omega$$

$g(t, i_b)$ is described in Section 2.

APPENDIX B

VALUES USED IN THE SIMULATION OF THE ONE-COIL MODEL

(a) The Capacitances, Inductances and Resistances

$$\left. \begin{array}{l} C_g = 5.28 \times 10^{-8} \text{ F} \\ C_s = 6.17 \times 10^{-8} \text{ F} \end{array} \right\} \quad C_e = 17.62 \times 10^{-8} \text{ F}^*$$

$$\begin{array}{l} L_b = 5.5 \times 10^{-6} \text{ H}^* \\ L_c = 11.113 \text{ H} \\ L_d = 8 \times 10^{-6} \text{ H} \\ R_d = .0425 \end{array}$$

*These values are slightly different than the values given for the MFTF coil in Appendix A. The values given there are:

$$\begin{array}{l} C_g = 8.44 \times 10^{-8} \text{ F} \\ C_s = 1.96 \times 10^{-8} \text{ F} \\ L_b = 2.7 \times 10^{-6} \text{ H} \end{array} \quad C_e = 12.36 \times 10^{-8} \text{ F}$$

The value of R_d used in the tests of the magnet was half this value, .02125 ohms.

(b) The Values Used in the Simulation of the Breakers

For a Breaker that Opens in Approximately $6 \times 10^{-6} \text{ s}$

I_b amperes	G_b (ohms)	I_b amperes	τ seconds
0	10^{-6}	0	10^{-6}
5950	10^{-6}	5980	10^{-5}
5960	10^{-4}	6000	10^{-6}
5970	10^{-2}		
5990	10^{-1}		
6000	10		

For a Breaker that Opens in Approximately 6×10^{-5} s

I_b amperes	G_b (ohms)
0	10^{-6}
5780	10^{-6}
5820	10^{-5}
5860	10^{-4}
5900	10^{-3}
5920	10^{-2}
5950	10^{-1}
5970	1
6000	100

I_b amperes	τ seconds
0	10^{-5}
5800	10^{-5}
5900	10^{-4}
6000	10^{-5}

For a Breaker that Opens in Approximately 6×10^{-4} s

I_b amperes	G_b (ohms)
0	10^{-6}
50	10^{-6}
100	10^{-5}
150	10^{-4}
400	.05
1000	.4
4000	1
5600	10
5900	100
6000	1000

I_b amperes	τ seconds
0	10^{-5}
500	5×10^{-5}
1000	5×10^{-5}
3000	10^{-4}
5000	5×10^{-5}
6000	5×10^{-5}

For a Breaker that Opens in Approximately 3.5×10^{-3} s

I_b amperes	G_{b-1} (ohms)
0	10^{-6}
25	10^{-5}
50	10^{-4}
100	10^{-3}
200	10^{-2}
300	10^{-1}
400	.4
1000	1.5
3000	5
4000	10
5200	35
5600	50
5900	300
5950	500
6000	600

I_b amperes	τ seconds
0	6×10^{-4}
500	4×10^{-4}
1000	2×10^{-4}
3000	10^{-5}
4000	10^{-4}
5000	2×10^{-4}
6000	3×10^{-4}

APPENDIX C

VALUES USED IN THE SIMULATION OF THE TEN-COIL MODEL

The values used in the simulation of the ten-coil model are exactly the same as those derived in Appendix A. For convenience they are listed below.

The same values were used for the breaker model as those listed for the one-coil model in Appendix B.

The following terms are defined by the circuit diagram of the ten-coil model, Figure 7, and the circuit diagram of the external circuits, Figure 9(c).

$$C_{so} = 1.385 \times 10^{-9} \text{ F}$$

$$C_{go} = 13.087 \times 10^{-9} \text{ F}$$

$$L_{10} = .17123 \text{ H}$$

$$\text{Mutual inductance between adjacent coils} = .1579 \text{ H}$$

$$\text{Mutual inductance between coils one coil apart} = .1445 \text{ H}$$

$$\text{Mutual inductance between coils two coils apart} = .1312 \text{ H}$$

$$\text{Mutual inductance between coils three coils apart} = .1178 \text{ H}$$

$$\text{Mutual inductance between coils four coils apart} = .1045 \text{ H}$$

$$\text{Mutual inductance between coils five coils apart} = .0912 \text{ H}$$

$$\text{Mutual inductance between coils six coils apart} = .0777 \text{ H}$$

$$\text{Mutual inductance between coils seven coils apart} = .0644 \text{ H}$$

$$\text{Mutual inductance between coils eight coils apart} = .0511 \text{ H}$$

$$C_{ge} = 12.4 \times 10^{-9} \text{ F}$$

$$C_{se} = 19.5 \times 10^{-9} \text{ F}$$

$$L_b = 2.7 \times 10^{-6} \text{ H}$$

$$L_d = 8 \times 10^{-6} \text{ H}$$

$$R_d = .0425$$

APPENDIX D

THE SCEPTRE PROGRAMS

The Sceptre Representation of the Cybernetic Arc Model

The Sceptre code requires that the differential equation, Equation 1, describing the breaker be simulated as an electric circuit. Figure A1 shows the circuit used.

Unless the static value of breaker conductance G_b is below a certain value, a false equilibrium point is reached. These values, which depend on the breaker current, are plotted for the MFTF coil in Figure A2.

In order to illustrate the working of the breaker simulation, Figures A3 to A6 show the time records of the breaker resistance, breaker conductivity, and breaker time constant for a breaker opening time of 6×10^{-5} s in the one-coil model. These figures correspond to the voltage and current plots in Figures 18 and 19. The Sceptre program for this simulation immediately follows the figures.

$$\begin{array}{lll} N_{ca} & -- & g(t) \\ E_A & -- & G(i) \\ R_A(i)C_A & -- & \tau(i) \end{array}$$

E_A and R_A are Dependent on the Current Through the Breaker

FIGURE A1.
The Circuit Simulation of the Equation
Representing the Circuit Breaker

FIGURE A2.

The Maximum Allowable Value of the Circuit Breaker Conductance G_b as a Function of Circuit Breaker Current I_b .
 $R_d = .0587$ ohms

FIGURE A4.

The static conductivity of the breaker, as represented by E_A in Figure A1,
for a breaker opening time of approximately 6×10^{-5} s

FIGURE A5.
The breaker conductivity, as represented by V_{CA} in Figure A1,
for a breaker opening time of approximately 6×10^{-5} s

FIGURE A6.
The breaker time constant, as represented by $R_A(t)$ in Figure A1,
for a breaker opening time of approximately 6×10^{-5} s

Sceptre Simulations of the Coil Models

The following pages contain the Sceptre programs for the simulation of the one and ten-coil model for simultaneous opening of the breaker and for an opening time of approximately 6×10^{-5} s.

S C E P T R E NETWORK SIMULATION PROGRAM

VERSION CDC 4.5.2 5/76
82/03/04. 16:39:19.

COMPUTER TIME ENTERING SETUP PHASE-

CPA .248 SEC.
PP 0.000 SEC.
IQ 0.000 SEC.

CIRCUIT DESCRIPTION

ONEB3, THE SIMPLEST CIRCUIT , WITH THE BREAKER
ELEMENTS

C1,1-0=5.28E-8
C2,2-0=5.28E-8
CC,1-2=6.17E-8
CA,104-102=1.
R30,3-0=.0425
R40,4-0=.0425
RB,2-5=EQUATION REC(VCA1
RA,103-104=TABLE TOW(ILB)
LD1,1-3=8.0E-6
LD2,2-4=8.0E-6
LC,1-2=11.113
LB,5-1=5.5E-6
EA,102-103=TABLE STAG(ILB)

OUTPUTS

RB,1RB,VLC,ILC,ILD1,ILD2,EA,VCA,RA,PLOT

FUNCTIONS

EQUATION REC(A)=(1.0/ABS(A))

TABLE STAG

0.1E-6 5780,1.E-6, 5820,1.E-5, 5860,1.E-4, 5900,1.E-3,
5920,1.E-2, 5950,1.E-1, 5970,1, 6000,100

TABLE TOW

0.1E-5 5800,1.E-5, 5900,1.E-4, 6000,1.E-5

INITIAL CONDITIONS

ILC=6000, VCA=1000, ILB=6000

RUN CONTROLS

CHECK MUTUAL MATRIX

PLOT INTERVAL=20

MAXIMUM PRINT POINTS=1000

STOP TIME=5.E-4

MAXIMUM INTEGRATION PASSES=4.E+5

END

SYSTEM NOW ENTERING SIMULATION

COMPUTER TIME AT TERMINATION OF SETUP PHASE-

CPA 1.079 SEC.

Sceptre Program 1

Simulation of the one-coil model with a breaker
opening time of approximately 6×10^{-5} s

S C E P T R E NETWORK SIMULATION PROGRAM

VERSION CDC 4.5.2 5/76
82/05/26. 08:53:59.

COMPUTER TIME ENTERING SETUP PHASE-

CPA .260 SEC.
PP 0.000 SEC.
IO 0.000 SEC.

CIRCUIT DESCRIPTION

TENWO MAY 25 82, THE TEN COIL MODEL WITH MUTUAL INDUCTANCE, WITHOUT !
THIS CIRCUIT USES THE VALUES GIVEN IN THE APPENDIX
ELEMENTS

C1,1-0=13.087E-8
C2,2-0=13.087E-9
C3,3-0=13.087E-9
C4,4-0=13.087E-9
C5,5-0=13.087E-9
C6,6-0=13.087E-9
C7,7-0=13.087E-9
C8,8-0=13.087E-9
C9,9-0=13.087E-9
C10,10-0=13.087E-9
C11,11-0=13.087E-8
C12,1-2=1.385E-9
C13,2-3=1.385E-9
C14,3-4=1.385E-9
C15,4-5=1.385E-9
C16,5-6=1.385E-9
C17,6-7=1.385E-9
C18,7-8=1.385E-9
C19,8-9=1.385E-9
C20,9-10=1.385E-9
C21,10-11=1.385E-9
CP,1-11=19.5E-9
CGL,1-0=12.4E-9
CGR,11-0=12.4E-9
R31,12-0=.0425
R32,13-0=.0425
LD1,1-12=8.E-6
LD2,11-13=8.E-6
L1,1-2=.1712
L2,2-3=.1712
L3,3-4=.1712
L4,4-5=.1712
L5,5-6=.1712
L6,6-7=.1712
L7,7-8=.1712
L8,8-9=.1712
L9,9-10=.1712
L10,10-11=.1712
M12,L1-L2=.1579
M13,L1-L3=.1445

Sceptre Program 2

Simulation of the ten-coil model with
instantaneous opening at the breaker

```

M14,L1-L4=.1312
M15,L1-L5=.1178
M16,L1-L6=.1045
M17,L1-L7=.0912
M18,L1-L8=.0777
M19,L1-L9=.0644
M110,L1-L10=.0511
M23,L2-L3=.1579
M24,L2-L4=.1445
M25,L2-L5=.1312
M26,L2-L6=.1178
M27,L2-L7=.1045
M28,L2-L8=.0912
M29,L2-L9=.0777
M210,L2-L10=.0644
M34,L3-L4=.1579
M35,L3-L5=.1445
M36,L3-L6=.1312
M37,L3-L7=.1178
M38,L3-L8=.1045
M39,L3-L9=.0912
M310,L3-L10=.0777
M45,L4-L5=.1579
M46,L4-L6=.1445
M47,L4-L7=.1312
M48,L4-L8=.1178
M49,L4-L9=.1045
M410,L4-L10=.0912
M56,L5-L6=.1579
M57,L5-L7=.1445
M58,L5-L8=.1312
M59,L5-L9=.1179
M510,L5-L10=.1045
M67,L6-L7=.1579
M68,L6-L8=.1445
M69,L6-L9=.1312
M610,L6-L10=.1178
M78,L7-L8=.1579
M79,L7-L9=.1445
M710,L7-L10=.1312
M89,L8-L9=.1579
M810,L8-L10=.1445
M910,L9-L10=.1579
J1,1-11=TABLE 1
OUTPUTS
VC1,VC2,VC3,VC4,VC5,VC6,VC7,VC8,VC9,VC10,VC11,PL0T
FUNCTIONS
TABLE 1
0,6000.,5.E-6,6000.,5.E-6,0.,100.E-6,0.
RUN CONTROLS
CHECK MUTUAL MATRIX
PLOT INTERVAL=.5E-4
MAXIMUM PRINT POINTS=500
RUN INITIAL CONDITIONS
STOP TIME=5.E-5
END

```

Sceptre Program 2 (continued)

Simulation of the ten-coil model with
instantaneous opening at the breaker

S C E P T R E NETWORK SIMULATION PROGRAM

VERSION CDC 4.5.2 5/76
82/06/17. 09:43:36.

COMPUTER TIME ENTERING SETUP PHASE-

CPA .222 SEC.
PP 0.000 SEC.
IO 0.000 SEC.

CIRCUIT DESCRIPTION

TENCOIL MAY 25 1982, THE TEN COIL MODEL WITH MUTUAL INDUCTANCE, WITH TH
THIS CIRCUIT USES THE VALUES GIVEN IN THE APPENDIX
APPROXIMATE BREAKER OPENING TIME 6E-5

ELEMENTS

C1,1-0=13.087E-9
C2,2-0=13.087E-9
C3,3-0=13.087E-9
C4,4-0=13.087E-9
C5,5-0=13.087E-9
C6,6-0=13.087E-9
C7,7-0=13.087E-9
C8,8-0=13.087E-9
C9,9-0=13.087E-9
C10,10-0=13.087E-9
C11,11-0=13.087E-9
C12,1-2=1.385E-9
C13,2-3=1.385E-9
C14,3-4=1.385E-9
C15,4-5=1.385E-9
C16,5-6=1.385E-9
C17,6-7=1.385E-9
C18,7-8=1.385E-9
C19,8-9=1.385E-9
C20,9-10=1.385E-9
C21,10-11=1.385E-9
CP,1-11=19.5E-9
CGL,1-0=12.4E-9
CGR,11-0=12.4E-9
R31,12-0=.0425
R32,13-0=.0425
LD1,1-12=8.E-6
LD2,11-13=8.E-6
L1,1-2=.1712
L2,2-3=.1712
L3,3-4=.1712
L4,4-5=.1712
L5,5-6=.1712
L6,6-7=.1712
L7,7-8=.1712
L8,8-9=.1712
L9,9-10=.1712
L10,10-11=.1712
M12,L1-L2=.1579

Sceptre Program 3

Simulation of the ten-coil model with a breaker opening
time of approximately 6×10^{-5} S

```

M13,L1-L3=.1445
M14,L1-L4=.1312
M15,L1-L5=.1178
M16,L1-L6=.1045
M17,L1-L7=.0912
M18,L1-L8=.0777
M19,L1-L9=.0644
M110,L1-L10=.0511
M23,L2-L3=.1579
M24,L2-L4=.1445
M25,L2-L5=.1312
M26,L2-L6=.1178
M27,L2-L7=.1045
M28,L2-L8=.0912
M29,L2-L9=.0777
M210,L2-L10=.0644
M34,L3-L4=.1579
M35,L3-L5=.1445
M36,L3-L6=.1312
M37,L3-L7=.1178
M38,L3-L8=.1045
M39,L3-L9=.0912
M310,L3-L10=.0777
M45,L4-L5=.1579
M46,L4-L6=.1445
M47,L4-L7=.1312
M48,L4-L8=.1178
M49,L4-L9=.1045
M410,L4-L10=.0912
M56,L5-L6=.1579
M57,L5-L7=.1445
M58,L5-L8=.1312
M59,L5-L9=.1178
M510,L5-L10=.1045
M67,L6-L7=.1579
M68,L6-L8=.1445
M69,L6-L9=.1312
M610,L6-L10=.1178
M78,L7-L8=.1579
M79,L7-L9=.1445
M710,L7-L10=.1312
M89,L8-L9=.1579
M810,L8-L10=.1445
M910,L9-L10=.1379
CA,104-102=1.
RA,103-104=TABLE TOW(ILB)
EA,102-103=TABLE STAG(ILB)
RB,14-1=EQUATION REC(VCA)
LB,11-14=5.4E-6
OUTPUTS
IL1,IL2,IL3,IL4,IL5,IL6,IL7,IL8,IL9,IL10
VC1,VC2,VC3,VC4,VC5,VC6,VC7,VC8,VC9,VC10,VC11,PLOT
RB,IRB,ILD1,EA,VCA,RA,PLOT
FUNCTIONS
EQUATION REC(A)=(1.0/ABS(A))
TABLE STAG
0,1.E-6, 5780,1.E-6, 5820,1.E-5, 5860,1.E-4, 5900,1.E-3,
5920,1.E-5, 5950,1.E-1, 5970,1, 6000,100
TABLE TOW
0,1.E-5, 5800,1.E-5, 5900,1.E-4, 6000,1.E-5

```

Sceptre Program 3, page 2

Simulation of the ten-coil model with a breaker opening
time of approximately 6×10^{-5} s

```

INITIAL CONDITIONS
  IL1=6000, IL2=6000, IL3=6000, IL4=6000, IL5=6000,
  IL6=6000, IL7=6000, IL8=6000, IL9=6000, IL10=6000,
  VCA=1000, ILB=6000
RUN CONTROLS
  CHECK MUTUAL MATRIX
  PLOT INTERVAL=20
  MAXIMUM PRINT POINTS=1000
  STOP TIME=5.E-4
  MAXIMUM INTEGRATION PASSES=4.E+5
END

```

SYSTEM NOW ENTERING SIMULATION

```

COMPUTER TIME AT TERMINATION OF SETUP PHASE-
CPA      2.022 SEC.
PP       0.000 SEC.
IO       0.000 SEC.

```

Sceptre Program 3, page 3

Simulation of the ten-coil model with a breaker opening
time of approximately 6×10^{-5} S