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SWITCHING TRANSIENTS IN A SUPERCONDUCTING COIL

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Abstract

A study is made 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 performance tests on the MFTF Yin-yang coils.

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.

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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 lightly damped resonant circuit. Even a small disturbance has the potential to excite a large amplitude oscillation with voltages that could damage the insulation.

In most applications the largest disturbance experienced by the magnet 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. A fast dump protects the magnet by transferring an appreciable portion of the magnet's stored energy to the 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 [1] who identified and described the behavior. The only reported damage from high frequency, high voltage oscillations was described by Gabriel and Burkhart [2]. They conducted experimental and analytical investigations that showed the unexpected failure of a superconducting coil was due to this source. Recently, Chowdhuri [3] 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 [4]. Therefore, superconductivity is of little consequence. In addition, an iron core coil can always be converted to an equivalent air core coil [4].

The main differences between power transformers and superconducting coils are in their modes of operation. A 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 1958 Abetti [5,6] gave excellent reviews and bibliographies of what constitutes the main body of the literature. Two supplements followed in 1962 [7] and 1964 [8]. 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 [9] 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 [10], Heller and Veverka [11] and Greenwood [12]. 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 [4]. 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. If there is no restrictions on how switching is carried out, it is possible to control the amplitude of the switching transients by controlling the switching process. This is the main topic of this paper.

Lumped Parameter Models of the Coil and its External Circuits

A schematic diagram of a superconducting coil and the circuits connected to it is shown in Figure 1. During normal operation the fast dump circuit breaker is closed. A fast dump begins when the circuit breaker opens, 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 [illegible] is opposed by the inductance of the resistor and the connecting cables, triggering a transient that excites the coil resonances.

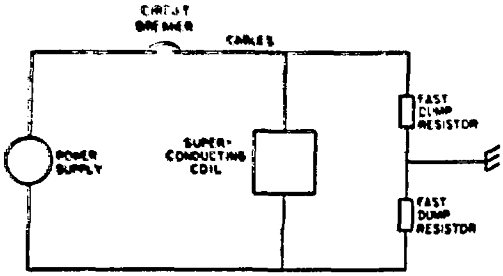

Figure 1. The Coil and its Associated Circuits

Figure 2 shows a circuit model in which the distributed inductance and capacitance of the system is replaced by lumped parameters. L_d and R_d represent the dump resistor and its associated cables while L_b and R_s represent the power supply. The capacitance C_{ge} is the combined capacitance of the cables and coil terminals to ground; C_{se} is the capacitance across the coil.

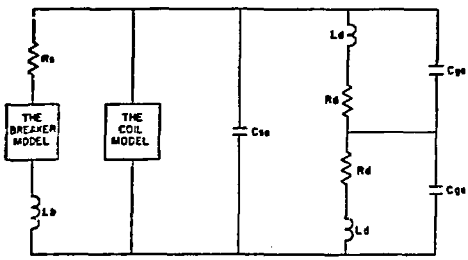

Figure 2. A Circuit Model of the External Circuits

The Coil Model

The superconducting coil is a three dimensional distributed network of capacitance and mutually coupled inductance. In some respects the coil resembles a transmission line, but models based on transmission lines either do not take mutual coupling into account or are too complex for practical computation. In order to fit the practical limitations of computers, models with lumped capacitance and inductance are used.

A lumped parameter model should exhibit the important features of the device it represents. In this application the most important factor is the voltage to ground, which is the voltage that determines the insulation requirement. The temporal and spacial description of the transient is of interest, but does not bear directly on the design of the insulation. Unfortunately, there is no known method of forming a lumped model of the coil with a behavior that corresponds to the coil itself. It is necessary to proceed pragmatically, using as a guide, analysis, numerical experimentation, and the experience of past investigators.

Two models of differing complexity are used in this study: one in which the coil is divided into ten segments and the other in which the coil is represented by a single inductance. The one coil model consists of a single inductance with shunt capacitance and capacitance to ground at each end of the coil.

The ten-segment model, which is shown in Figure 3, contains ten mutually linked inductances with mutual and self-inductances derived from field calculations on the MFTF coil.

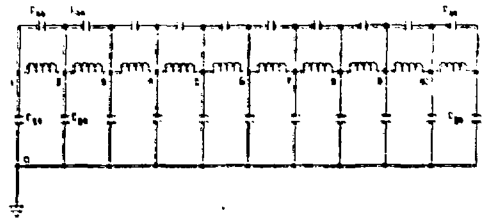

Figure 3. The Ten-coil Model of the Superconducting Coil

Ten self-inductances lead to 45 mutual inductances. The model contains two kinds of capacitance, shunt capacitance and capacitance to ground. The shunt capacitance represents the turn-to-turn and layer-to-layer capacitance of the winding. The capacitance to ground represents the capacitance of the outer conductors to the case.

The Circuit Breaker

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 [13]. The circuit to which the breaker is connected is important in determining the behavior.

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 [14].

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 [15]. 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, 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 [16] 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:

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

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 can be determined if two sets of time records containing that current are available.

As Smith found in his 1974 [16] 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 breaker's behavior. Our tests of the magnets did not yield enough information to satisfactorily derive the parameters. 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 dependance 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 breaker's voltage and current. After a few trials it was possible to match the computer simulations to the tests.

Analysis of the One-coil Model

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 principal modes of external behavior and leads to an understanding of the factors affecting the critical voltages.

For the purposes of analysis the one-coil model can be simplified further. The center-tapped 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 4. In this circuit L is the inductance of the superconducting coil and Ce is a combination of the shunt capacitance and the capacitance to ground and R_b is a combination of the power supply and breaker resistance. The other elements are the same as those in Figure 2.

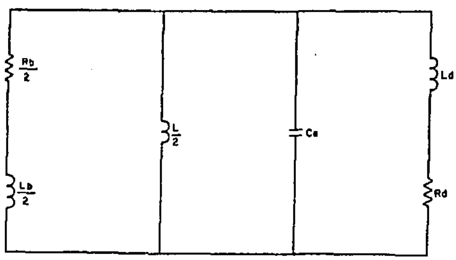

Figure 4. A Simplified Model of the Coil and its External Circuits

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

$$s^3 + \frac{R_d}{L_d} s^2 + \frac{L + L_d}{C_e L L_d} s + \frac{R_d}{C_e L L_d} = 0$$

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. The characteristic equation of this circuit is

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

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

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

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. The peak voltage can be calculated as follows:

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

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.

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. The circuit is made amenable to analysis by replacing the coil with a constant current source and neglecting the effect of series inductance in the breaker path. Applying these simplifications to Figure 4 and designating the fixed breaker resistance as R_b results in the following characteristic equation.

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

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

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

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.

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 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.

Measurements on the MFTF Coils

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 measurement showed that the circuit breaker opened in about 3 ms. As the breaker opened the current decreased smoothly from the initial current to zero. The voltage record contained no evidence of oscillation and no trace of peaking.

Computer Simulations

Because of economic and technical factors it was not possible to make measurements over a range of breaker and circuit characteristics. The effect of these factors was determined by means of computer simulations, using the test data as a starting point.

Computer results that corresponded to the test results were obtained by trial and error adjustment of the cybernetic arc model of the circuit breaker. The static conductivity and the current dependent time constant were changed until the simulated current in the coil matched the observed current. More rapid interruptions of the current were investigated by changing these parameters to shorten the interruption interval while at the same time maintaining a smooth transition of the coil current from rated current to zero.

Table 1.

The Effect of Breaker Opening Time on the Transient Voltage to Ground for the One-coil Model

Breaker opening time (S)	The nature of the response	Maximum voltage to ground (V)	Frequency (Hz)
instantaneous	almost sinusoidal	[illegible]	[illegible]
6×10^{-6}	almost sinusoidal	19,959	136,00
6×10^{-5}	single pulse	1,880	---
6×10^{-4}	single pulse	340	---
3.5×10^{-3}	overdamped	255	---

The effect of breaker opening time on the peak voltage to ground and on the transient shape is shown in Table 1 for simulations using the one coil model[17]. Instantaneous opening of the breaker, the only case amenable to analysis, serves as a check of the computer results. The analytical results, a peak voltage to ground of $I\ L_d/C_e$ and a frequency of $1/2\ L_d/C_e$ Hz agree exactly with the simulations. Increasing the interruption time decreases the peak voltage and changes the shape of the voltage response. For rapid openings the response is oscillatory. As the opening time increases the response degenerates into a monopulse and then into an overdamped response with no peaking. At 3.5 ms the voltage approaches the dc fast dump voltage of 255 V with no overshoot.

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	Max. amplitude of voltage to ground (volts), a single pulse
C	L_d	L_b	1880
C	.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	.18 L_b	1880
C	L_d	3 L_b	1895

A computer study was made of how the peak voltage to ground is affected by the inductance of the dump resistor, the capacitance of the circuit, and the inductance of the breaker. The breaker opening time was held at 6×10^{-5}s. The results are summarized in Table 2. In the first line of the table the circuit parameters are the same as in Table 1. In each of the succeeding lines one of the three circuit parameters is increased or decreased in accordance with the factors shown. The dump inductance L_d and the capacitance C have been varied over a range of 1 to 4; while the range for the breaker inductance is greater.

As the results show, only the inductance associated with the dump resistor has a significant effect on the peak voltage to ground. As the dump inductance increases so does the peak voltage. The circuit capacitance and the breaker inductance have little effect on the peak. This result cannot be predicted from analysis of the simple circuit in which the breaker opens instantaneously. For this case the peak voltage depends on the ratio of L_d to C_e.

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.

The waveform at the terminals of the ten-coil model is similar to that observed with the one-coil model. For an instantaneous opening of the breaker the wave is almost sinusoidal, with a frequency and peak value that can be predicted from the analysis of the one-coil model. For slower opening time, the external waveshape obtained from the one-coil and ten-coil models are undistinguishable. This leads to the conclusion that the one-coil model is sufficient to predict the maximum voltage to ground.

The interior voltages of the ten-coil model demonstrate the existence of the circuit's additional natural frequencies. In the interior the external circuit parameters do not predominate and waveshapes consisting of many damped sinusoidal components are visible.

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.

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, the transients are similar to those that occur when the opening is instantaneous. Increasing the opening time causes the shape of the transient to change from a sinusoid to a monopulse. As the breaker opening time decreases so does the amplitude 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.

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 at slower breaker speeds. Inductance in series with the breaker is also of negligible importance.

In final conclusion, theory, computer simulation and measurements have demonstrated that the transients induced by a fast dump of a superconducting coil can be damped by making the time taken to interrupt the circuit long relative to the system's natural frequencies. During a slow opening of the breaker, energy which is otherwise stored in the circuit capacitance is dissipated in the breaker arc.

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