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ALTERNATIVE POWER SUPPLY AND DUMP RESISTOR CONNECTIONS FOR SIMILAR, MUTUALLY COUPLED, SUPERCONDUCTING COILS

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Abstract

Alternative methods of connecting similar mutually coupled coils to their power supplies and dump resistors are investigated. The circuits are evaluated for both operating and fault conditions. The factors considered are the voltage to ground during a dump, short circuits, open circuits, quenches, and failure of the protection system to detect a quench. Of particular interest are the currents induced in coils that remain superconducting when one or more coils quench. The alternative connections include combined power supplies, individual dump resistors, combined resistors and series and parallel dump resistors. A new circuit that contains "coupling" resistors is proposed. The coupling resistors do not affect normal fast dumps but reduce the peak induced currents while also reducing the energy rating of the dump resistors. Another novel circuit, the series circuit with diodes, is discussed. The MFTF-B central cell solenoids are used as an example.

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Introduction

The operation of a number of magnetically coupled superconducting coils with similar currents poses problems not encountered in the operation of a single coil. The problem is a new one and little guidance is found in past examples. In this paper the technical and economic attributes of a number of alternative methods of connecting the coils are examined.

The MFTF-B central cell solenoids are used as an example [1]. These consist of twelve coils, each with 600 turns and a mean diameter of 5 m. At the maximum current of 2800 A the field is about 1.5 T. The self-inductance is 3.6 H and the mutual inductance is substantial, 1 H between adjacent coils.

In the planned operating modes the current in the end coils is slightly larger than the current in the center coils. The four coils at the center have the baseline, or smallest current flowing through them. The coils are supplied from thyristor power supplies with freewheeling parallel diodes that allow the current to freely circulate in the forward direction but which block reverse flows. There are two modes of discharge, a slow dump and a fast dump. A fast dump is used under fault conditions. The purpose of a fast dump is twofold: to remove energy that might otherwise heat the magnet; and to eliminate low resistance paths through the power supplies. The speed of the dump is limited by the voltage to ground caused by the dump.

The power supplies, coils, breakers and dump resistors are connected using standard cables. The resistance of the connections, which is the order of milliohms, is an important factor in some of the fault conditions.

Conditions That Endanger the Coils

The coils can be damaged by excessively high temperature, voltage, or current [2,3,4]. A high temperature can melt the solder, cause deterioration of the electrical insulation, or even melt the conductor. High voltage to ground or between one part of the coil and another can damage the electrical insulation. The electromagnetic forces are proportional to the squares of the currents. Determination of the worst-case combination of forces is a complex subject. However, from the standpoint of the electrical designer, the imperative is to reduce the maximum currents in the coils to the smallest values possible.

A current larger than the operating current can be induced in a superconducting coil when the field changes rapidly due to a quench of neighboring coils. The size of the induced current depends on how the coils, dump resistors, and power supplies are connected.

Fault Conditions

Several fault conditions must be considered in evaluating the alternative connections: short circuits, open circuits, quenches, and failure of the quench protection system.

Short circuit currents do not depend on the connection used. Nonetheless it is useful to consider them because the short circuit currents constitute the largest currents that can be induced in the coils. The worst-case occurs when one coil has a superconducting short and the current in the other coils is decreased to zero. The maximum short-circuit current, which is reached when all of the other currents are zero, depends only on the initial currents and inductances and not on the rate of decay of current.

Short circuit currents are responsible for some of the peak fault forces. In the MFTF-B solenoids the short circuit currents are approximately twice the operating current.

The open circuits that pose a danger are those in the path of the inductive current. An open circuit in the coil, current leads, or in the dump resistor during a dump are in this category. There are two hazards: overvoltage of the coil and heating, fire, and melting at the site of the open circuit.

Failure of the cooling will trigger a quench. During a quench there is a buildup of the coil resistance and a decay of the coil current. The decay is roughly an order of magnitude faster than the decay during a fast dump. There are two dangers to the coils. The temperature of a quenched coil may become too hot. And second, a quenching coil or group of coils may induce relatively large currents in neighboring coils.

Developing a mathematical model for a quench is difficult. Rather than attempt to model a quench exactly, a conservative model is used in the computer studies. The entire superconductor is assumed to go normal at the same time, shifting the bulk of the current from the superconductor to the copper at 4.2 K. All of the heat generated is assumed to be stored in the metallic mass. The temperature rise of the copper is calculated taking into account the dependency of the resistivity and specific heat on temperature. Heat stored in the insulation or lost to the coolant is neglected.

The currents induced by a quench are increased if the quench protection system fails and the coils do not fast dump. A quench of one or more coils induces voltages in the remaining superconducting coils that tend to sustain or increase the current. The current that results depends on the resistance of the available conducting paths. In general there are two conducting paths, through the dump resistors [illegible] through the power supplies. The paths through the power [illegible] ... Therefore, the peak current [illegible] when the coils quench and the protection system fails [illegible] the power supplies [illegible].

A method of reducing the peak induced current, if the protection system fails, is to increase the resistance of the power supply loops. However, power lost in the power supply is a continuing expense.

The peak currents are affected by the way in which the coils are connected to the power supplies and the dump resistors. If each coil has its own supply the supply is directly connected across the coil. However, in other connections, additional coils, resistors, and diode paths can be interposed between the coil and the low resistance paths through the power supplies.

A Classification of the Connections

Many ways of connecting the coils have been proposed and considered [5]. The major features of these circuits are encompassed in the four circuits shown in Figures 1 through 4 and listed below. The circuits are divided into three groups which have similar functional and physical properties.

Coils with individual, parallel dump resistors

1. One main power supply
2. Coupling resistors

Coils with combined, parallel dump resistors

3. One group of twelve coils

Coils with series dump resistors

4. With diodes, breakers for each coil

In the first category, each coil has its own dump resistor *permanently* connected in parallel with it. In the second category, individual dump resistors are not used; a dump resistor serves a number of coils connected in series. In the third category, the dump resistors are connected in series with the coils instead of in parallel and a breaker shorts out the resistors during normal operation.

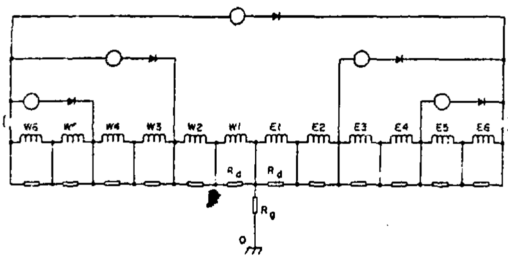

Figure 1. Coils with individual, parallel dump resistors, one set of breakers

Coils With Individual Parallel Dump Resistors, One Main Power Supply

The circuit with individual parallel dump resistors, which is shown in Figure 1, combines the advantage of individual dump resistors with a minimum number of power supplies, cable runs and breakers. A main power supply provides the current shared by all twelve coils. The additional current in the two pairs of end coils comes from smaller trim supplies arranged to minimize the current and power rating of each supply.

The two breakers will not open simultaneously; therefore the consequences of one opening before the other must be considered. The first breaker to open interrupts the current through the eight coils at its end. The current through the four coils at the other end can still flow through the trim supplies. Opening the second breaker interrupts this path.

The maximum voltage to ground is the voltage caused by a fast dump. This voltage occurs just after the first breaker opens. At this moment the voltage from the ground resistor to one end of the series string of coils is 6 V_C, where V_C is the coil voltage. Therefore, the maximum voltage to ground is 6 V_C.

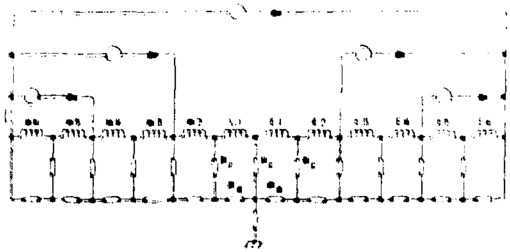

Figure 2. Coils with individual, parallel dump resistors, with coupling resistors

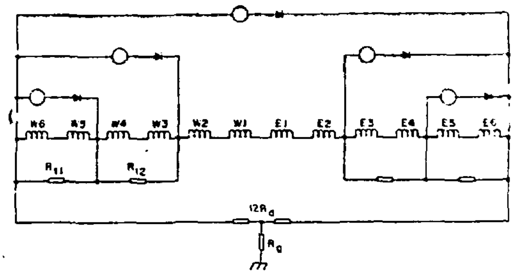

Figure 3. Coils with combined, parallel dump resistors, one group of twelve coils

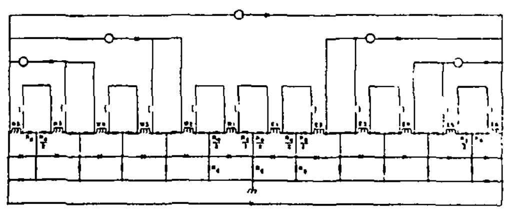

Figure 4. Coils with series dump resistors, with diodes and breakers for each coil

The other two factors that affect the safety of the coils are temperature and peak current. Table 1 is a summary of simulation results for the W1 [illegible] coils. Included in the [illegible] energy absorbed by a dump resistor. While not a factor in the coil safety, the dump resistor energy is a factor in the cost of the protective system.

Table 1.

The maximum induced current, maximum coil temperature, and maximum energy absorbed by a dump resistor during a fast dump and for critical fault conditions for the circuit with individual parallel dump resistors.

Dump resistance = .0291 ohms.

	The max. peak current / operating current	The max. final temp. K	The max. energy absorbed by a dump resistor MJ
FAST DUMP			
all coils super-conducting	1.00	4.2	27.8
all coils quench	1.00	67	8.3
all except W1 quench	1.12	66	36.0
POWER SUPPLIES CONNECTED			
all except W3 quench	1.47	76	25.3
all except W5 and W6 quench	1.31	76	1.7
only W1 quenches	1.11	80	117.6

As Table 1 shows, the critical values of peak current, temperature, and energy absorbed by a dump resistor occur when the power supplies are connected. The fast dump results are included for comparison purposes.

For a fast dump with all coils either quenched or all coils superconducting there is no current peaking. The maximum current during a fast dump occurs when all coils except W1 or E1 quench. W1 and E1, positioned as they are at the center of the string of coils have the maximum coupling to the other coils. The currents induced in coils further away from the center, when all other coils quench, is less.

The additional energy transferred to W1 by its quenching neighbors must eventually be absorbed by its dump resistor. As a result, the maximum energy absorbed by a dump resistor during a fast dump is the energy absorbed by W1's dump resistor when all other coils quench.

If the protective measures fail, and the power supplies remain connected during a quench, the low resistance paths through the power supplies cause the induced current to be higher than during a fast dump. The exact result depends on a complex combination of the available conduction paths and the mutual coupling between the superconducting and quenched coils. Coils near the center have the largest coupling. However, the coils at the end have conductive paths through the trim power supplies.

When the power supplies are connected, the maximum current occurs if the superconducting coil is coil 3. During a fast dump, coil 1 has the maximum induced current. Another critical situation occurs when the two end coils, coils 5 and 6 remain superconducting and the remainder quench. These two coils are virtually short-circuited by the other trim supply. Although the coupling between the [illegible] and the other coils is not as large as for other pairs, the peak currents are larger.

The maximum energy is absorbed by a dump resistor when the power supplies remain connected and only one coil quenches. As the quench resistance builds up, the current is forced from the coil to the alternative path through the dump resistor. The final quench resistance is an order of magnitude greater than the dump resistance, consequently most of the current is diverted to the dump resistor. The worst-case occurs when one of the four center coils quenches and the other coils remain superconducting. The quench attenuates the current in the center four coils but the currents in the two groups of four end coils are free to circulate through the trim supplies and are not attenuated. The energy stored in the center four coils is absorbed by the quenched coil and its dump resistor.

Table 2.

The relationship between the fast dump voltage to ground, the maximum induced current and the dump resistance.

The maximum current is induced when all coils except W3 quench and the power supplies are connected.

Dump resistance ohms	peak current / operating current	Time of peak current s	Voltage to ground V
.5 x .0291	1.64	88	250
.0291	1.47	73	500
2 x .0291	1.32	60	1000

In choosing the resistance of the dump resistor there is a tradeoff between induced current and voltage to ground during a fast dump. Increasing the dump resistor decreases the induced current by increasing the resistance of the path around which the current flows. However, increasing the resistance increases the voltage to ground. Table 2 shows the nature of the tradeoff for the solenoids. The voltage to ground is proportional to the resistance. However, since the resistance of the power supply is the dominant factor, the induced current is only weakly dependent on the dump resistance. Therefore, increasing the dump resistance is a relatively ineffective way of reducing the induced current.

Coils With Individual, Parallel Dump Resistors, Coupling Resistors

The circuit, which is shown in Figure 2, is similar to the previous one except that resistors, called coupling resistors, are placed between the coils and the dump resistors. The purpose of the coupling resistors is to decrease the peak induced current in the coils.

When the currents in the two coils are equal, the coupling resistors have no effect. If the current in one coil is larger than the other, a voltage is produced across the coupling resistor that tends to decrease the larger current and increase the smaller one.

During a fast dump the coil currents are equal except for the small trim currents. Coupling resistors adjacent to the coils with equal current have no effect on the dump, while those at the trim power supply lines have only a small effect.

During a quench the current in a quenched coil decays rapidly, causing it to be smaller than the current in adjacent coils. The coupling resistors tend to sustain the current in the quenched coil and decrease the current in the adjacent superconducting coils. This decreases the peak

Table 3.

[illegible]

	The max. peak current oper. current	The max. final temp. K	The max. energy absorbed by a dump resistor MJ	The max. energy absorbed by a coupling resistor MJ
FAST DUMP				
all coils super-conducting	1.00	4.2	27.4	0.0
all coils quench	1.00	67	8.3	0.0
all except W1 quench	1.00	68	19.9	4.3
POWER SUPPLIES CONNECTED				
all except W3 quench	1.21	79	6.0	12.2
all except W5 & W6 quench	1.24	76	6.0	0.8
only W1 quenches	1.11	88	18.3	20.0

induced current at the price of increasing the energy absorbed by the quenched coil.

The effect of coupling resistors is illustrated by the results in Table 3 which show the induced current, temperature and energy to resistors for a circuit in which the coupling resistance equals the dump resistance. Table 3 can be compared with Table 1, a similar table for the circuit without coupling resistors.

As Table 3 shows, the coupling resistors have little effect during a fast dump for the two cases: all coils remain superconducting and all coils quench. Under these circumstances the current in all of the coils at any time is the same except for the trim currents and differences due to differing mutual inductance. However, if there is a fast dump when all coils quench except coil W1 the effect of the coupling resistor is appreciable. The coupling resistors eliminate the peak current induced in coil W1. In addition, the energy absorbed by coil W1's dump resistor is greatly reduced.

Table 4.

The effect of coupling resistance on the peak current and final temperature when all coils except W3 quench.

The power supplies are connected with diodes to ensure unidirectional current flow. The peak current occurs in W3. The maximum temperature rise is in W4. R_d = .0291 ohms.

Value of coupling resistance	peak current / operating current	Final temp. of W4 K
0	1.54	74
.5 R_d	1.30	76
R_d	1.21	79
2 R_d	1.12	83
3 R_d	1.07	85
5 R_d	1.03	87

[illegible]

Table 4 shows the effect of the size of the coupling resistor on the current induced in coil W3 when all of the other coils quench. In the circuit without coupling resistors this peak, which is 54 percent higher than the operating current, is the highest current encountered in this circuit when the protection system fails. Coupling resistors equal to the dump resistors reduce the peak to 21 percent higher, while coupling resistors five times the dump resistors virtually eliminate the peak. The price paid for this reduction is an increase in the final temperature of the quenched coils adjacent to coil W3.

Table 5.

The effect of coupling resistance on the peak current and final temperature when all coils quench except W5 and W6.

Value of coupling resistor	peak current / operating current		Time of peak current		Final temperature	
	for W5	for W6	W5 s	W6 s	W4 K	W3 K
0	1.31	1.15	94	130	67	73
R_d	1.24	1.22	84	118	69	72
2 R_d	1.22	1.22	86	111	69	72
5 R_d	1.21	1.22	92	102	70	72

As Table 5 shows, the coupling resistors are not as effective in reducing the peaks in coils W5 and W6 when this pair remains superconducting. Only a single coupling resistor links the rest of the coils to the pair, which is shorted by the outer trim supply. The peak current in coils 5 and 6 can be decreased by increasing the resistance of the trim power supplies. Ordinarily, increasing the resistance of a power supply is prohibitively expensive because the operating current must flow through the additional resistance causing substantial energy losses. However, the trim currents are small and the expense is tolerable.

The use of coupling resistors substantially reduces the physical size and cost of the dump resistors. Placing coupling resistors in the circuit increases the resistance of the alternative path for the current. The current can flow either through the coil itself or through a series combination consisting of a coupling resistor, a dump resistor, and a coupling resistor. Consequently, more of the current tends to flow through the coil and less through the dump resistor. The result is that the final temperature of the coil is higher but the energy absorbed by the resistors is less.

Coils With Combined, Parallel Dump Resistors

Instead of having individual dump resistors, a number of coils can share the same dump resistor. In the most extreme application of this concept, all twelve coils, which are connected in series, share the same dump resistor as shown in Figure 3. Since the two pairs of end coils have slightly different currents, it is necessary to connect separate dump resistors across these pairs. The resistance of these trim dump resistors is high, and their effect on the circuit is small.

The circuit is simple and inexpensive, but the main reason for considering it is the low peak induced current. When eleven coils quench, the remaining superconducting coil is in series with the quenched coils. [illegible] the total flux [illegible] the current in all coils is the same. As a result, there is no [illegible] of the [illegible] even when the power supplies remain connected.

Unfortunately, the connection has several disadvantages. An open circuit in any of the coils, the connecting wires or the dump resistor affects all coils. A less obvious disadvantage is that a quench of one or two coils causes both a high temperature in the quenched coils and a high voltage to ground.

The high temperature is a direct result of the series connection of the coils. The current, which flows through all coils, transfers energy from the superconducting coils to the quenched coils, raising the temperature of the quenched coils. The worst-case occurs when any one of the coils quench and the rest remain superconducting.

A high voltage to ground is also induced by a quench of a small number of coils. A quench places a large resistance in the series path, causing the rate of change of current to be high. The reactive voltages across the superconducting coils are large and add together. The highest voltage to ground is produced by a quench in the coils at one end of the string of solenoids.

Coils With Series Dump Resistors and Diodes

Figure 4 shows a circuit in which the dump resistors are connected in series with the coils and diodes are connected across each coil-resistor group. During charging and normal steady-state operation, all of the breakers are closed, shorting the dump resistors. The current flows from the main supply and through the twelve coils in series. The reactive voltages of the coils during charging and the resistive drops during normal operation back bias the diodes, causing them to act like open circuits.

Opening the breakers removes the shorts across the dump resistors and the low resistance paths through the power supplies. The current is constrained to flow through the dump resistors and the diodes, which act like short circuits.

An advantage of the circuit is that, during a fast dump, the voltage to ground is as low as possible, only half the coil voltage. After the breakers have opened, the voltage rise across each coil is opposed by the voltage drop across the resistors on each side of the coil. As a result, the voltage from one coil-resistor combination to another is almost zero. The grounding resistors constrain the voltage at the midpoints of the dump resistors to be zero. Therefore, the voltage at the center of the coils is also zero, with the maximum voltage of half the coil voltage at the ends of each coil.

In contrast to the circuits with parallel resistors, the voltage to ground does not depend on the order in which the breakers open. As each breaker opens only current in its coil is interrupted. The diodes associated with the closed breakers remain back biased, maintaining the current through their coils. As each breaker opens, it has across it a voltage equal to the voltage IR_d. Each switch, therefore, interrupts or redirects the energy stored in a single coil. This is in marked contrast to the circuit breakers in circuits with parallel dump resistors. In these circuits the first circuit breaker to open must redirect most of the energy stored in all the coils.

Another advantage of series dump resistors over parallel dump resistors is that the power supply can have a smaller power rating. In the parallel circuit, current flows through the dump resistors when the magnet current is being changed. In the series circuit the dump resistors are shorted by the breakers and absorb no power.

The induced current during a fast dump is the same as the induced current in the circuit with parallel dump resistors. After all of the breakers are open, the series circuit consists of a number of disjoint loops. Each loop contains a coil connected to the dump resistors on either side of it by a conducting diode. This electrical configuration is exactly the same as the circuit with parallel resistors during a fast dump.

The behavior of the circuit when one or more coils quench and the power supply remains connected is not easily characterized. Under these circumstances the diodes can switch on and off. However, simulations show that for similar dump voltages to ground the series circuit is superior to the parallel one.

The main disadvantage of the series circuit is the cost of the additional circuit breakers and cables. In the MFTF-B project it was necessary to locate the diodes and breakers at a distance from the coils, making the cost prohibitive.

Conclusions

Cost and a number of technical factors must be considered in choosing between the many alternative ways of connecting a number of similar, mutually coupled, superconducting coils. When inductive coupling is strong, a key factor in determining the forces on the connecting structure may be the currents induced in neighboring coils when some of the coils quench. This current depends on the connection.

In the MFTF-B project the circuit with coupling resistors has been chosen for the central solenoids. The coupling resistors reduce the induced current and the circuit meets the project's technical and cost criteria. The series circuit with diodes has a technical advantage but is more costly.

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