Superconducting Fault Current Limiter

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Prepared by
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ELECTRIC POWER RESEARCH INSTITUTE

SUPERCONDUCTING FAULT CURRENT LIMITER

EPRI EL-329
(Research Project 328)

Final Report

December 1976

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ABSTRACT

We have considered the use of a superconducting element as the active part of a fault current limiter for the power utilities. Such a device is technically feasible over a wide range of parameters for the required electrical power source and material properties of the superconductors available. Limiting is achieved by driving the superconductor into its resistive state and commuting the current into a shunt resistor. For a three phase, 145 KV (RMS), 2 KA (RMS) line, the total cost excluding installation in the power system and shunt resistor is approximately $300,000. The specific advantages and disadvantages are indicated, as well as the outstanding problems to be tackled next.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This document is a preliminary report on the evaluation of superconductors for use as fault current limiters for the electrical utilities. This report is an outgrowth of our project on Superconducting Rectifier Development (EPRI TD-245). The primary conclusion of this report is that a superconducting fault current limiter (SCFCL) is indeed technically feasible over a wide range of parameters for the required electrical power source and the material properties of the superconductors available. The economic feasibility will depend ultimately on the value of such a device to the power companies, but the SCFCL must also be competitive in price with alternative types of FCL's.

We have extensively studied the design of a SCFCL for a 145 KV (RMS), 2000 amp three phase line with available fault current of 45 KA (RMS). We have shown that a long superconducting flim in parallel with a 3.65 Ω resistor can adequately limit the fault current, in all circumstances, to 20 KA (RMS) and a first loop peak current of 28 KA. This is accomplished by switching the superconductor from its lossless state into its resistive state, which is much greater than 3.65 Ω. Choosing reasonable values of the material properties of the superconductor ρ_N and J_c, we find a compatible solution with a length 600 meters, a width 6.7 cm and a thickness of 2 microns. This can be accommodated in a cryostat which is two cubic meters. The total capital cost of such a device for <u>all</u> three phases is estimated to be just under \$300 K with a yearly operating cost of about \$30 K.

The specific advantages of a SCFCL are: solid state switching; low losses; fast recovery; and no problems at high voltages. Along with these are some disadvantages of low temperatures and the need for external sensing. In addition, it should be pointed out that the economics of a SCFCL is even more attractive when used in an electrical distribution system already utilizing superconductive or cryogenic equipment (such as generators, transformers or transmission lines). In this case the cost of the high current feedthroughs with necessary refrigeration is entirely eliminated. A savings of roughly <u>half</u> the estimated cost would result.

The following are the outstanding problems to be considered: (1) fabrication of the superconducting element on a suitable substrate; (2) switching the superconductor to the resistive state; (3) recovery time; and (4) high current, high voltage feedthroughs.

The most important problem in (1) is finding a flexible insulating substrate since suitable superconductors are presently available. For this reason, items (2) and (3) could be considered first or concurrently using existing substrates. If research on all these items come to a successful conclusion, the construction of an operating SCFCL prototype can be contemplated.

Section 1

INTRODUCTION

In recent years the electric utility industry has needed to expand its facilities to meet the ever growing demands of its customers. This growth has led to the installation of larger blocks of generation, transmission and distribution facilities, which has resulted in an increase in the available short circuit current. In the past, most systems have withstood extraordinary overloads because of the conservative design margins built into power equipment. At the rate potential fault currents are growing, those margins may no longer be technically possible or economic to build. In addition, existing circuit breakers have reached or are approaching the limits of their capability to interrupt fault currents successfully. There is a clear need for a device which can limit the fault current to such a value that existing circuit breakers can interrupt service until the fault is cleared.

The importance of the problem dictates that novel approaches to a solution should be explored. Several possible solutions to this problem are presently being considered, with moderate success. In particular, the use of a superconductor as a fault current limiter has been given consideration by ITE Corporation (EPRI TD-130). Their conclusions were that superconductors become attractive at voltage levels above 550 KV. In a recent report by Argonne National Laboratory (EPRI TD-245) it was pointed out that this prospect should be explored in greater detail, in view of the conclusions of that report on a similar superconducting switch used as a rectifier. The present report has been generated as a result of that conclusion and funded with money from that contract (EPRI No. 31-109-38-3130L).

The work statement for this report is to establish the feasibility and conceptual design for a superconducting fault current limiter (SCFCL).

Feasibility

Determine analytically the technical feasibility of a 145 KV, three-phase superconducting fault current limiter with the following parameters:

1. 2000 amperes rms continuous load current
2. Source system capable of delivering 45,000 amperes rms fault current with an X/R ratio of 20
3. Fault current limited to 20,000 amperes rms steady state
4. Initial loop of fault current limited to 35,000 amperes crest. (Assume adequate sensing and fast bypass switches are available if necessary.)

Determine expected costs of such a fault current limiter in enough detail that extrapolations can be made for other operating parameters.

Conceptual Design

Develop sketches and other descriptions of a conceptual design of the FCL specified above. List assumptions and describe all sensitive design parameters.

In the following sections of this report we present the results of a feasibility study of a superconducting fault current limiter for use in existing (and proposed) power distribution networks. This preliminary study shows that there are no major unsolved problems relating to the technical feasibility and that the estimated cost is reasonable.

In section 2 we discuss fault currents. Section 3 summarizes the principle of operation of our superconducting fault current limiter, while section 4 shows the results of analysis (including an extensive computer program) to demonstrate the technical feasibility. Section 5 provides a conceptual design on which the cost analysis of section 6 is based. Section 6 includes the results of extending the design parameters to higher and lower voltages and currents, etc. Section 7 summarizes the conclusions of this preliminary report by pointing out the important problems to be addressed next.

Dave Fowler assisted greatly in writing sections 4 (especially the computer program) and section 6. Ken Gray participated in these and wrote the other sections.

Section 2

FAULT CURRENTS

Fault currents occur when a electrical power line is shorted. Because most power networks are fed by constant voltage sources, currents much larger than the normal load can be drawn under short circuit conditions. This is especially true when many different sources are interconnected for system stability. These large currents can cause damage to buss lines, transformers and generators due to the heat dissipated and perhaps more importantly due to the increased forces caused by the large currents.

The most important short circuits occur close to the source, because the transmission lines have sufficient inductance to limit the fault currents if they are far from the source (perhaps tens of miles). For this reason lightening strikes are the predominant cause of short circuits since substations and users are generally far enough from the primary source. The electrical energy of the lightening does not directly cause the fault current, but is responsible for ionizing the air, which causes a low impedance electrical path to ground for the generated power. With no source of additional electrical power feeding the arc, it takes the order of 0.1 to 0.5 seconds for sufficient recombination of the ionized air to estinguish the arc. Hence the fault current from 60 Hz ac as well as dc will maintain the arc indefinitely unless the circuit is broken. As mentioned in the introduction, circuit breakers are insufficient to handle the fault currents for proposed new installations, and hence the need for a fault current limiter.

Because lightening is the major contributor, faults can occur many times on one line during a short storm whereas the line can be fault free for a long period of time between storms. However, because the strikes occur at varying distances from the source, and the transmission line has an inductive impedance, the fault currents vary in magnitude. In Figure 2-1 we show the probability P(I) of a fault current being larger than or equal to I as a function

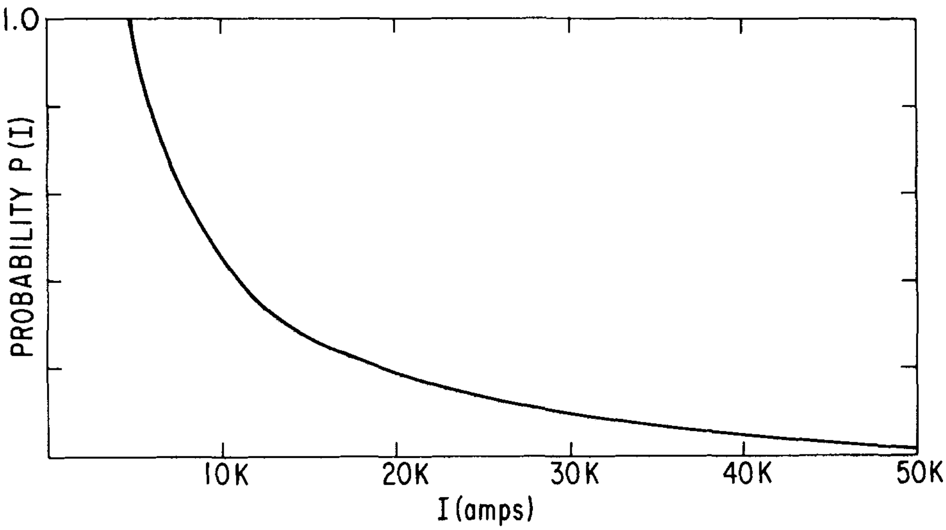

Figure 2-1

of I. This is given analytically (for $P(I) < 1$) by $P(I) = (V_P/I - Z_S)/Z_L$ where V_P is the peak voltage to ground for each phase, Z_S is the source impedance and Z_L the total line impedance. The phase to phase RMS voltage (145 KV in our case) is larger than V_P by $\sqrt{3/2}$ so V_P = 118 KV. The source impedance Z_S is obtained from the design parameters to be V_P divided by the <u>peak</u> available fault current, i.e., $\sqrt{2}$ x 45 KA in our case. The inductive impedance per mile times the length gives Z_L. We have assumed a 25 mile line, an inductive impedance of 0.9 Ω per mile, and find that Z_S is 1.86 Ω. The frequency of operation of a fault current limiter will therefore depend on the threshhold current for which it has to operate. Our design parameters require a threshhold below the maximum allowable peak current of 35 KA. For design purposes we further assume a diabolical worst case of 20 strikes per storm. For a threshhold current of 20 KA this implies a maximum of 34 operations per storm, but for less than about 5 KA we would require the full 20 operations per storm in the worst case. These considerations will dictate constraints on the threshhold current of any fault current limiter.

Section 3

PRINCIPLE OF OPERATION

The operation of our proposed SCFCL is based on a principle of commuting the current from the superconductor into a shunt resistor. The shunt resistance is large enough to limit the short circuit current to the desired level. A schematic design of this is in Figure 3-1. During normal load with no fault,

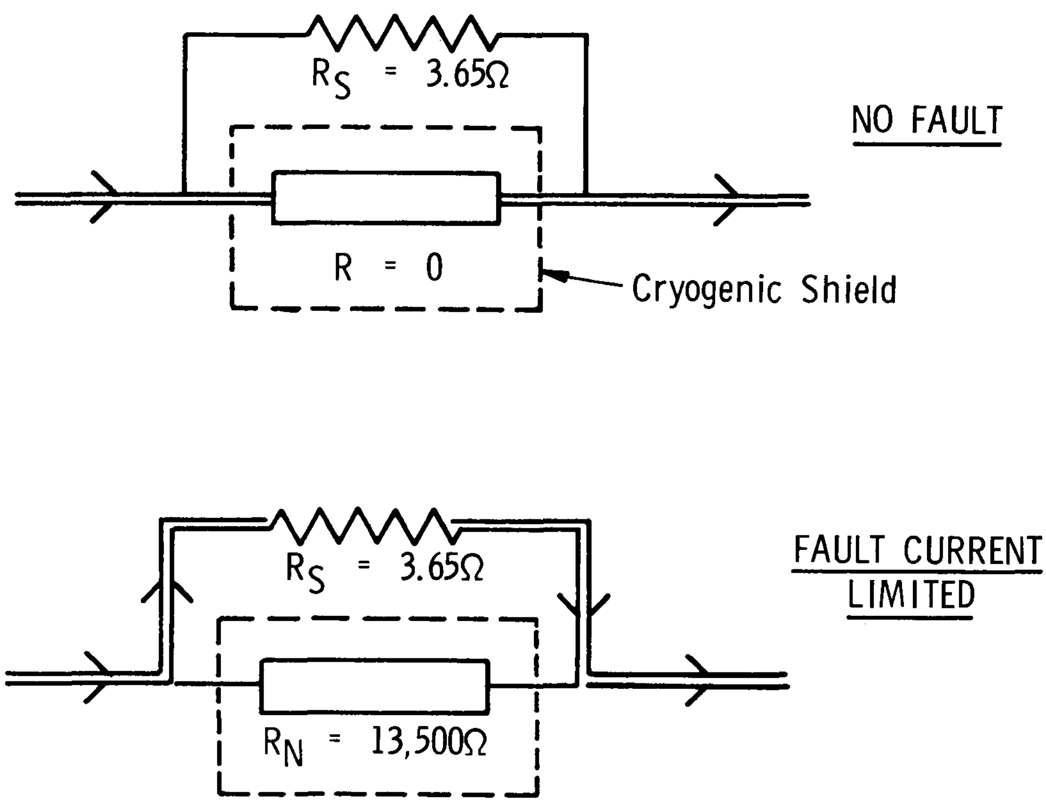

Figure 3-1

the superconducting element has zero resistance, and carries the load current. Under fault conditions, the superconductor is switched into its normal, resistive state (R_N = 13,500 Ω) to commute the current into the shunt resistor (R_S = 3.65 Ω). The crucial part of this process is the means by which the superconductor is switched into (and out of) its normal resistive state.

At this point a slight digression into the properties of superconductors is in order. Most metals and alloys become superconductors if their temperature is lowered sufficiently. That is, below the transition temperature T_c which ranges in value from absolute zero to about 20 K. One property of the superconducting state is zero resistance to the flow of electrical current and hence zero dissipation or losses. However, if either the temperature, magnetic field or current are raised above their critical values, a resistive state occurs. An important feature of this transition is that it only involves the electrons in the metal and there is no movement of atoms. As a consequence of this, switching can occur an indefinite number of times with no damage or degrading of the switching element. Likewise carrying a steady current below the critical current causes no electromigration or other damage to the superconducting element. In other words the SCFCL cannot be worn out.

The phase diagram of a typical type I superconductor is shown in Figure 3-2 The transition to the normal state can be achieved either by raising the field $H_c(T)$ at constant temperature T or by increasing the temperature above T_c (usually at H = 0 for simplicity). Raising the current in the supercontuctor I_{sc} above I_c will also produce a resistive state, however, this will not be effective for a SCFCL. The reason is that during a fault the current must be

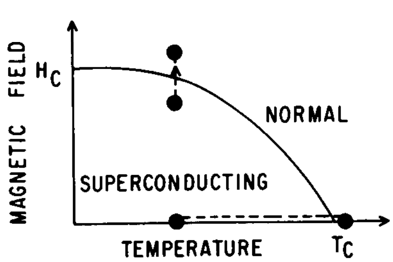

Figure 3-2

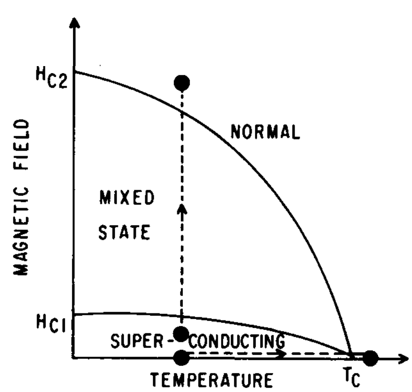

Figure 3-3

commuted into the shunt resistor so I_{sc} would fall below I_c. An intermediate state of resistance (less than R_N) would result with a large dissipation in the partially normal superconductor. Since one pays a heavy penalty for removing heat at low temperatures this is intolerable. Of course if the temperature of the superconducting element increases above T_c due to the dissipation, $I_c(T)$ goes to zero, as $H_c(T)$ does, and the element is completely normal. For our purposes, however, we will consider this to be thermal switching. For type I superconductors the magnetic field changes for switching may be as small as 100 Oe and temperature changes are about 5 K.

A switch made out of a superconducting element is ideal in the "on" or conducting state since the resistance is zero for dc and very small for ac. The problem is in the "off" or resistive state where the resistance cannot easily be made large. This is because the element is made from metals which are typically very good conductors. The resistance of the element will depend on the geometrical sizes and the normal state resistivity ρ_N of the material used. The cross sectional area is predetermined by the critical current density J_c and the maximum current you wish to pass through the element without switching. The cross sectional area is minimized and resistance maximized if J_c is as large as possible. Although the resistance can be made indefinitely large by increasing its length, this leads to other problems. We find the operation of a SCFCL requires a normal state resistivity of the order of 100 to 300 μΩcm, which is quite high for a metal. Such metals do exist, and they are superconductors, however, for $\rho_N \gtrsim 2$ μΩcm, all superconductors are type II. Figure 3-3 shows one important difference between type I and type II. For type II superconductors there are two critical fields $H_{c1}(T)$ and $H_{c2}(T)$ between which is a very lossy mixed state. To compound this, for large ρ_N, the upper critical field is very large and lower critical field small, so the switching field is virtually the full value of $H_{c2}(T)$. For our design value of ρ_N = 300 μΩcm, $H_{c2}(T)$ is necessarily greater than 200 KOe and magnetic field switching can be completely ruled out. The high field associated with large ρ_N is a consequence of the Gor'kov-Goodman relation. Fortunately, however, thermal switching is unchanged for high ρ_N and therefore it is this method that we propose for operating the SCFCL.

At this time we should point out another analysis of superconductors for switching electrical power. This is the ANL report on the superconducting recifier (EPRI TD-245). In that report, magnetic switching was ruled out for the same reasons, but more details are contained therein. However, in that report, thermal switching was also ruled out. The primary difference in the SCFCL, which makes that conclusion inapplicable, is the repetition rate of the switch. In the 60 Hz rectifier, there was a trade off between obtaining sufficient temperature increase with tolerably small losses and having a fast thermal response time for recovery back to the superconducting state. Because the SCFCL will operate a few times a year instead of 60 times a second, both of these conflicting constraints can be relaxed. Recovery times for the SCFCL can be about 25 msec, compared to 1 msec for the 60 Hz rectifier. More importantly the heat loss per switching event can be much higher for the SCFCL.

One way to thermally switch the superconducting element into the normal state is with external heat. Resistance heaters or intense light irradiation are examples of methods. Another method relies on the heat generated in the superconducting element itself to maintain T above T_c. In this case the device could be in principle, at least, self sensing, in a manner similar to that described previously. When the current exceeds the critical current, the ensuing dissipation raises the temperature above T_c. An additional necessary condition is that the heat dissipated in the fully normal state is sufficient to keep T above the normal value of T_c (i.e., T_c for zero field and zero current). In that case the superconductor will not switch back to a partially resistive state (with intolerable dissipation) after the current is commuted into the shunt resistor. This is an important factor which has been overlooked in other conceptual ideas for a superconducting switch.

Another important, and also previously neglected feature of switching a superconductor by imposing a greater than critical current or field is that experimentally the break down is not ideal. Resistance does not appear uniformly, but is first seen at the inevitable weakest spot of the superconductor. The resulting hot spot will not necessarily propagate throughout the superconductor before the local temperature increases to the point of fusing the superconducting line. Because of this problem, it is unlikely that self sensing can be used in a SCFCL. An external pulse (of current, field or heat) must quickly switch the majority of the superconductor into a highly resistive state to limit the current throughout the device.

There are several methods of applying an external pulse to trigger the SCFCL. Resistance heating would be very difficult because of the need for high voltage insulation. This is not a problem for radiation heating. However, the long length of the superconducting element as well as the complicated geometry (see section 5) dictate other severe problems. These geometrical limitations also adversly affect the prospect of a magnetic field initiating the breakdown. The use of an additional current pulse seems to be the simplest and most economical alternative. The possible approaches to the problem of triggering the transition will be discussed in far greater detail in section 4. The transition must occur in a short enough time so that the whole element switches before hot spots become too hot. This must be triggered at a current level reasonably below the minimum critical current so that no hot spot can develop before the triggering. A related problem is that of commutation time. Losses are intolerable if there is a high resistance in the superconductor element before the high current has been commuted into the shunt resistor. We will also address ourselves to this problem in greater detail in section 4.

We have stated above that a high normal resistivity ρ_N is necessary to keep the length of the superconducting element to a manageable size. This requirement precludes the use of usual metallic temperature stabilizers for the superconductor. Metallic stabilizers will lower the normal state resistance, but provide no additional current carrying capacity in the superconducting state. As in the case of the rectifier, thin superconducting films ($\sim$ 1 to 5 microns thick) provide intimate contact with the liquid coolant (liquid helium for example) to provide the necessary thermal stabilization. During normal operation (no fault) of a SCFCL this stabilization is not too important because we operate substantially below the critical current. However, for a fast recovery of the superconducting state after the fault is cleared, it is essential. More will be said about this recovery time in section 4.

This completes our very general description of the principle of operation of a SCFCL. The following sections will relate to specific designs and consider the feasibility and economics.

Section 4

TECHNICAL FEASIBILITY

The outline of the principle of operation of a SCFCL did not in any way determine if it was in fact technically feasible to build such a device. In this section we critically analyze the requirements to show that they can be met with presently available methods and materials. The calculations have been carried out as far as possible for such a preliminary report, and in section 7 we indicate improvements and extensions of these calculations which should be made.

Several points were raised in the last section which must be considered here. These relate to hot spots, commutation, the trigger pulse and the recovery time after a fault. The following additional questions were not explicitedly stated. Does the temperature go above T_c? How much above? What are the currents in the superconducting element and shunt resistor as a function of time after a fault? What is the effect of the phase angle at which the fault occurs? How much helium is converted to gas? How is it removed? How much are ac losses? Is there a reasonable set of parameters which will accomodate all of the above considerations?

The purpose of this section is to answer these questions as completely as possible. Further questions relating to cryogenics and external connections are deferred until section 5 in which a conceptual design based on the results of this section is presented.

The answers to many of these questions require a complete time evolution of the currents flowing and heat dissipated. Because the resistance of the superconductor is time dependent and the temperature of the superconductor is derived from an integral equation, analytic solutions cannot be obtained. The system is, however, amenable to a computer iteration. Unfortunately, some of the questions cannot be answered in this way, or have not yet been put into the computer program. In these cases, approximate solutions can serve to demonstrate the importance of the effects. In particular, the computer program does not incorporate a trigger pulse, but rather uses self switching. This will affect the heat dissipated for a few microseconds during switching. However, an improved, exact calculation requires a significantly more complex computer program and a detailed knowledge of the distribution of J_c along the superconducting element (which is hard to determine without recourse to some experiments which have not been performed). The total switching time for the self switching computer solution is almost the same as that which is required of the trigger pulse, and we will show that the helium losses during switching are a negligilbe fraction of the total, so that the results of the computer program are a very good approximation.

In sections 4.1 and 4.2, we address ourselves to the computer program and the questions that it can answer. The additional problems are then discussed in relation to the computer program in the sections which follow.

4.1 COMPUTER PROGRAM

As we mentioned before, we are interested in the time evolution of the current through the SCFCL and the shunt resistor after a fault occurs. The equivalent circuit, shown in Figure 4-1, can be represented by the following simple differential equation:

$$L\frac{dI}{dt} + IR = V_P \sin(\omega t + \alpha),$$

where L and R are the total series inductance and resistance in the circuit, V_P is the peak voltage to ground for each phase and α is the phase angle at which the fault occurs (t = 0). This equation can be solved analytically, except in our case where R is a function of time because of the switching of the superconducting element R_{sc}. The total resistance is given by

$$R = R_o + R_{sc}R_s/(R_{sc} + R_s).$$

We therefore use the following iteration procedure, which calculates the change δI in I during the time interval δt:

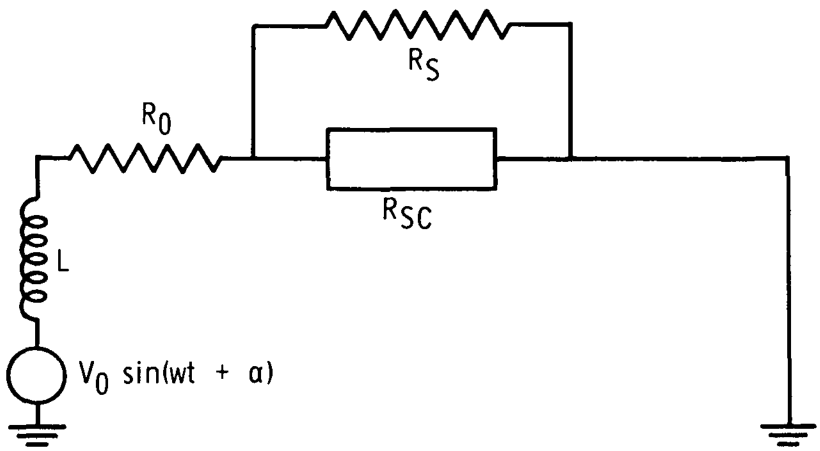

Figure 4-1

$$\delta I = (V_p \sin(\omega t + \alpha) - IR)\delta t/L,$$

where the time is stepped along in intervals of δt and I and R are the values obtained after the previous iteration.

Unfortunately, the determination of the time evolution of R_{sc} is not so easy. As was stated in section 3, when the critical current (I_{c1}) of a superconductor is exceeded, resistance appears. The question is how much, since the element does not immediately take on the full normal state resistance ($R_N = \rho_N \ell/dw$, where ℓ, d and w are the length, thickness and width of the superconducting element). If the temperature is kept constant, the resistance will continue to increase with current until I_{c2} at which point the full normal resistance is obtained. The exact nature of this behavior is poorly known because it is difficult to test this experimentally under isothermal conditions. For simplicity, we assume $I_{c2} = 1.5\ I_{c1}$ and use a linear interpolation for the resistance. More accurate knowledge of this dependence will not affect the results greatly for the following reason. The SCFCL will not be isothermal either, and the dissipation due to the onset of resistance causes its temperature to increase, so that both I_{c1} and I_{c2} decrease. (We assume both I_{c1} and I_{c2} follow the Ginzburg-Landau dependence $(1 - T/T_c)^{3/2}$ found to be valid for a wide variety of superconductors. High T_c superconductors have recently shown a $1 - (T/T_c)^2$ dependence, but the exact temperature dependence should not greatly affect our results.) The point is that as the temperature increases, I_{c1} decreases causing an even larger resistance (and dissipation) so that T_c is surpassed rather quickly.

There is a very important shortcoming in this procedure, in that it neglects hot spot instabilities. These are difficult to account for in the computer program, and we will discuss them in more detail in section 4.3.

This procedure does allow us to continue our calculation, using

$$R_{sc} = R_N\,(I_{sc} - I_{c2}(T) - I_{c1}(T)),\ \text{for } T < T_c$$

$$\text{and } R_{sc} = R_N,\ \text{for } T > T_c,$$

where $I_{sc} = I\,R_s/(R_s + R_{sc})$. We must solve these equations together to get R_{sc} as a function of I. We are inherently making another assumption of zero commutation time, about which we will say more in section 4.5.

Before the picture is complete, we must know the temperature in order to evaluate R_{sc}. Therefore an additional equation for heat flow is needed. The specific heat C_v per unit volume tells us the change in temperature for a given heat input E, such that

$$\frac{dE}{dT} = C_v \ell wd,$$

where dE is given by $(I_{sc}^2 R_{sc} - F)dt$ and F is the heat flux from the superconductor into the liquid coolant. Since C_v and F are nonanalytic functions and I_{sc} and R_{sc} are obtained iteratively, we clearly must do likewise for the change in temperature δT. The equation becomes

$$\delta T = (I_{sc}^2 R_{sc} - F)\delta t / C_v \ell wd.$$

For the specific heat we use the following theoretical expressions:

$$C_v = \gamma T + AT^3 \text{ for } T > T_c$$

$$= (3\gamma/T_c^2 + A)T^3 \text{ for } T < T_c$$

where γ and A are determined empirically, and we use values appropriate to niobium.

The heat flux F into liquid helium at T_o = 4.2 K is more complicated since there are two fundamentally different processes at the surface. For small heat flux, nucleate boiling (which happens when water boils in a pot) converts liquid to gas bubbles, which absorb the latent heat of the helium. For larger heat fluxes, film boiling occurs with a stable gas layer (film) forming between the metal surface and liquid, which acts as an insulator. Because of this insulation, a smaller heat flux is required to achieve a given ΔT, or a larger ΔT is associated with a given heat flux. Figure 4-2 shows the behavior of F for copper surfaces (from Cummings, D. R. and Smith, J. L., Bul. IIR Annex. 1966-5 p. 85). The transition from nucleate to film boiling occurs at about 1 K above T_o. For simplicity in the computer program we approximate this with a linear behavior above and below the transition region.

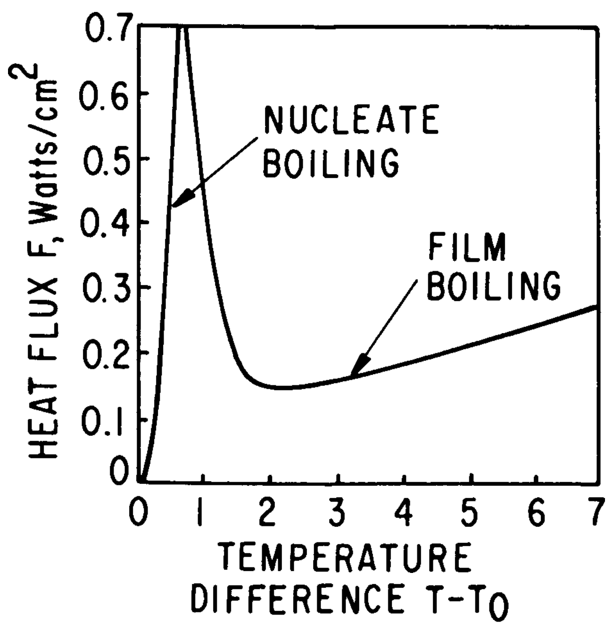

Figure 4-2

We now have a complete set of equations, and the order of the iteration is as follows. The change in current is computed using values of I and R from the previous iteration and the appropriate time t. Next R_{sc} and I_{sc} are determined using critical currents for the temperature of the previous iteration, and the helium boiloff for that interval is calculated. Finally a new temperature is determined for use in the next iteration. Step sizes of 10 μsec are used throughout, except during switching where it was found necessary to use a step of 0.1 μsec.

We also assume a room temperature switch which electrically isolates the superconducting element after the first zero crossing of fault current. The operation of this switch not only lowers the total liquid helium boiloff per fault, but also allows a longer time for the switch to recover back to the superconducting state so the circuit can be reconnected.

We thus have a calculation of the time evolution of the currents and temperature in a given SCFCL. The program also calculates the total helium boiloff, the effective gas layer thickness (assuming the total boiloff, converted into gas, were distributed uniformly on the surface area ℓw) and the thermal recovery time back to the superconducting state.

4.2 COMPUTER CALCULATIONS

This program can now be used to evaluate the performance of a SCFCL given certain parameters and conditions. In addition to the operating parameters set by EPRI in section 1, we must use values for the superconductor's material properties ρ_N, C_v, T_c and J_c, the geometrical shape ℓ, w and d (the product wd is determined by the desired maximum current, I_c, passed without operating the fault limiter and J_c), the shunt resistance and the phase angle α. We determine acceptable solutions as those with small helium boiloff ($\lesssim$ 10 liters/ fault; small gas layer thickness (<0.5 mm/fault), short thermal recovery time (τ_{th} < 25 msec), small volume for superconductor (volume including cooling and insulating channels $\lesssim 1\ m^3$), and a low maximum temperature (T_{max} < 100 K). Of course, ultimately cost is the determining factor, but the above gives a guide to practical devices.

It can be easily shown that zero phase angle has the maximum fault current and is the worst case, so subsequent calculations consider this possibility only. (Another difficulty occurs when the maximum fault current is just greater than I_{c1}. In this case, the element switches back to the superconducting state before the first zero crossing but without unduly large losses. The more important problem involving hot spots will be discussed later.) Experience with the program shows that changes in C_v and T_c, that you might expect from one material to another, have relatively little effect on the results. Even doubling T_c from 9 to 18 K left the qualitative behavior unchanged. On the other hand, it is clear that we want the maximum of ρ_N and J_c to minimize the volume, and we use values of 300 μΩcm and 3 x 10^6 A/cm^2 respectively. These have been reported for NbN and are presumably possible in Nb_3Sn and other materials if ρ_N can be increased by impurities.

The maximum current passed without switching the superconductor, I_c, is yet to be determined. Some insight can be gained by referring to Figure 2-1 which shows the probability of faults at a given current level. Clearly a large value of passed current dictates fewer operations, but a larger cross-sectional area and length. Adjusting these geometrical parameters allows a lot of flexibility in gaining an acceptable solution. As such there is not necessarily a clear cut optimum solution, even when cost is considered (see section 6).

As a check of the program, we calculated the fault current without a limiter. We get an asymmetrical current whose decay time is without 2% of the calculated L/R time. The solution approaches a steady state value of 45 KA (RMS) as it should. An example of a solution with and without the SCFCL is shown in Figure 4-3. For the case using the SCFCL, the current is limited to 20 KA (RMS) and conventional circuit breaker opens the entire circuit after 2-3

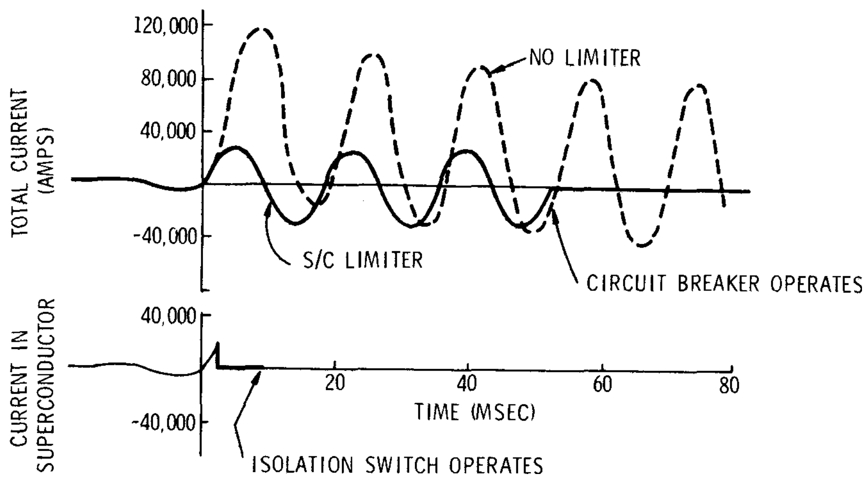

Figure 4-3

cycles. At the first zero crossing of the current in the superconducting element (figure 4-3), an isolation switch opens that circuit electrically isolating the superconductor and allowing it to recover to the ambient temperature $T_o = 4.2$ K.

Because the solutions to our equations are numerical, we cannot determine exact functional dependencies of the recovery time, helium loss, etc. on the geometric parameters. We can, however, interpret the data so that trends associated with changing these parameters can be visualized. Increasing the length of the superconductor, ℓ, has the advantages of shortening the recovery time, allowing the gas layer of helium to be thinner, boiling off less helium, lowering the temperature excursion of the superconductor, and increasing the normal resistance of the superconductor. Competing with these advantages are the increased costs for materials, fabrications and cryostat for large ℓ. Under all conditions of the other parameters, values of ℓ less than 200 meters seem unreasonable.

Making the samples thicker tends to counterbalance the changes due to increasing ℓ. To keep the same I_c the crosssection of the superconductor must remain the same, hence the width of the film, w, will decrease as will the total volume. This will increase the helium gas layer thickness, the recovery time and the maximum temperature excursion. Depending on the value of the length, the film thickness d can be varied from about 0.5 μm to almost 10 μm. Films much thinner than 0.5 μ may be too wide for economical production and thicknesses greater than 10 μm generally have recovery times too long.

As the critical current, I_c, is increased the width and therefore the volume must increase linearly. The larger surface area and an increase in helium boiloff offset one another to keep the helium gas layer fairly constant. The temperature excursion and the recovery time rise slightly. To assure that the SCFCL is not operated accidentally, I_c should be at least 4000 amps for a normal load current of 2000 A (RMS). An I_c of 28 KA, will pass all faults except those which damage equipment (our limit is 20 KA (RMS)), however, we are practically limited to less than this value because of the large lengths and crosssectional areas required for bigger I_c. For any given value of I_c in this range, however, acceptable values of ℓ and d are found.

The great flexibility in adjusting parameters makes the selection of a model system somewhat arbitrary. For the calculations that follow, we shall use the following parameters (in addition to those power distribution system parameters given by EPRI in section 1) when referring to our model system. They include: I_c = 4000 A; ρ_N = 300 μΩcm; $J_c = 3 \times 10^6$ A/cm^2; d = 2 microns; w = 6.7 cm (2-1/2 inches); ℓ = 600 meters. For this model, the normal resistance is 13,500 Ω, and the computer program calculates a helium loss of 1.1 liters per fault, a helium gas layer of 0.18 mm, a maximum temperature of about 20 K and a recovery time of about 15 milliseconds from the initiation of the fault.

4.3 HOT SPOTS

One important problem associated with an unstabilized superconductor is that a small region can go normal, dissipate $J^2\rho_N$ power per unit volume, and dramatically increase its temperature. In the case of the SCFCL, if one region has a significantly smaller J_c than the rest, it would go normal and dissipate the full $J^2\rho_N$ until other parts of the element switched, and J was reduced. If J is not reduced quickly enough, the element will fuse.

Unfortunately this cannot be easily modeled in the computer program. We do not know the distribution of J_c, and if we did, the program would be far more complicated because the temperature would be different at different points along the superconducting element. No attempt has been made to analyze this problem on the computer, however, it is straight forward to calculate the minimum time before fusing by neglecting the heat flux into the helium bath. we find a power dissipation per unit volume of $J_c^2\rho_N = 2.7 \times 10^9$ W/cm^3 or per unit area 2.7×10^5 W/cm^2. The power per unit area justifies neglecting the heat flux to the helium which is only 2 W/cm^2 for T ∿ 100 K. The enthalpy of niobium at 300 K (room temperature) is about 700 joules/cm^3, so that room temperature is reached in about 0.25 μ seconds! The melting temperature of 2400 K is reached in about 2 μ seconds! In order to avoid this catastrophe, the total resistance of the superconducting element must become substantially greater than R_s in less than 2 μ seconds.

The maximum rate of change of current, which occurs for the worst case fault at α = 0, is about 1.6×10^7 A/sec. This corresponds to only 32 amps in 2 μ seconds. With a critical current of about 4000 amps the total spread of I_c could be as much as 1000 amps so that self switching is not sufficiently fast to avoid fusing at a hot spot. Lowering J_c to 1×10^6 A/cm^2 will decrease the power dissipation per unit volume by a factor of 9. Although this increases the time until melting to 18 microseconds, it is unlikely that self sensing can achieve reliable operation. This is primarily because there will always be some faults whose maximum current is just above the critical current at the weakest point. These faults occur at different phase angles α or for shorts that are far removed from the source. For these, the rate of change of current will be much smaller than the maximum value we used in the above estimate. Because of this, a trigger pulse, described in the next section is necessary.

4.4 TRIGGER PULSE

The simplest trigger pulse is to discharge a capacitor across the superconducting element, as soon as a fault has been determined, but before the lowest critical current is reached. In this way I_c is quickly exceeded everywhere, before a hot spot can develop and fuse the line. To do so, we must pulse a few thousand amps through the SCFCL in a few microseconds ($\sim 10^9$ Amps/sec), depending on J_c. The voltage required will depend on the total inductance of the SCFCL. The superconducting element, bifilarly wound gives a contribution $L_{sc} = \mu_o \ell b/2w$, where b is the voltage insulation spacing -- typically about 0.5 mm. This inductance is about 2.5 μHy for our model, but the feedthroughs and internal connections may increase the total to about 20 μHy. The current pulse then requires a voltage $L_{sc} dI/dt \simeq 20 \times 10^{6}$Hy $\times 2000$ A/4 $\times 10^{6}$ sec = 10 KV and a capacitor of about 1 μF. This type of capacitor is easily obtainable, inexpensive and reasonably small sized. It would be discharged through a low inductance switch as shown in Figure 4-4 and dissipate a negligible 10 joules in the helium bath. The point is that this trigger pulse only initiates a

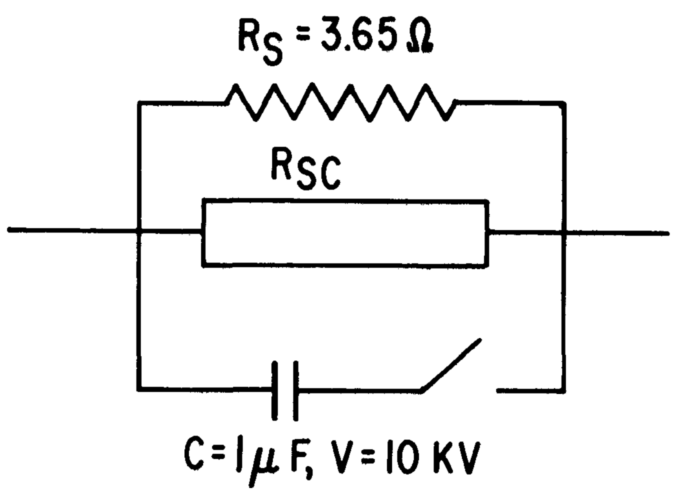

Figure 4-4

resistive state, but does so uniformly along the superconducting element. It is the fault current that provides the dissipation to increase T above T_c, and change R_{sc} to R_N, thereby commuting the current into the shunt resistor.

There are several problems with the operation of such a trigger device. The first, which is of less consequence, is that it involves electrical connections to a high voltage circuit in such a way that a different polarity capacitor must be used depending on the polarity of the fault current, i.e. the currents must add to quickly quench the superconductivity. This can be overcome by using two capacitors and switches, and perhaps more simply by one capacitor, charged by the opposite polarity of the line voltage each half cycle. The second problem has to do with the discharge switch, which must be fast enough and have a small inductance. The third problem is perhaps the most serious. As the trigger current increases, it is possible that at some point in time, a sufficient number of isolated regions will go normal, so that $R_N >> R_{sc} >> R_s$. In that case the additional trigger current will flow through the lower impedance shunt resistor and be ineffective at transforming the remaining superconducting regions into the normal state. The switch resistance will essentially stay at this value, lower than R_N, unless thermal propagation along the film can transform the superconducting regions. Barring this thermal propagation, there will be increased localized dissipation (more helium boiloff per fault) leading to larger temperature excursions (longer thermal recovery time) and wasted portions in the length of the switch which remain superconducting. The real magnitude of these problems are possibly best investigated experimentally (see section 7).

In view of this, we propose an alternative scheme which avoids all of the above problems. Although as we pointed out in section 3, it is impossible to completely magnetically quench into the normal state, a perpendicular magnetic field greater than H_{c1} will place the film uniformly in the lossy mixed state. This can also be viewed as uniformly lowering its critical current. At this point, uniform dissipation will cause a uniform transformation into the normal state.

The problems associated with magnetic switching have been thoroughly investigated in section 2.7 of the FINAL REPORT on Superconducting Rectifier Development (EPRI TD-245). The pulse power, the product of the voltage V_p and current I_p, necessary to pulse a field H over a volume v in a time τ_p is given by

$$I_p V_p = \mu_o H^2 v/\tau_p.$$

The volume of the superconducting elements is estimated at $1m^3$ in section 5, and for the proposed superconductors a field of about 300 Oe should be sufficient. If we assume a reasonable value of 4 microseconds for τ_p, we can evaluate the pulse power, and find it to be 2×10^8 watts. This means we need to supply our switching magnet with, for example, 20 KA at 10 KV, or some other combination depending on the design (H = kI) of the magnet. This pulse could be supplied for example from a single capacitor in the manner described earlier. The conceptual design of such a magnet is shown in section 5.

In conclusion, magnetic initiation of the switching is advantageous because of uniformity and electrical isolation from the high voltage circuit. The disadvantage is the cost and complexity of constructing the magnet.

4.5 COMMUTATION TIME

In all the previous calculations it was assumed that changes in the current distribution between the superconducting element and the shunt resistor occur instantaneously during switching. Due to the finite inductance in the loop containing the superconducting element and the shunt resistor, this is not strictly true. The effect of the inductance is to delay the commutation of current from the superconductor to the shunt by the L/R time of the loop.

We can determine a simple differential equation governing the commutation if we make the very reasonable assumption that the fault current is constant at I_c during the very short period of switching. We obtain:

$$(L_s + L_{sc})\dot{I}_{sc}/R_s + (1 + r_{sc}(t))I_{sc} = I_c,$$

where L_s and R_s are the inductance and resistance of the shunt and $r_{sc}(t)$ is the resistance of the superconducting element in units of R_s. Again as in section 4.1, we have a simple differential equation, but which cannot be solved analytically because of the time dependence of $r_{sc}(t)$. Of course it is a simple matter to solve for I_{sc} iteratively if we know $r_{sc}(t)$. However, at this point we are stopped from a complete solution, just as in the hot spot calculation, because we do not know the distribution of J_c. Knowledge of this would allow us to determine $r_{sc}(t)$ from the rate of rise of current (fault plus trigger pulse) during switching.

To get some idea of the importance of the commutation time, we solve a simple model where $r_{sc}(t)$ is given by at. We can then compare the exact solution, neglecting commutation, with the iterative solution including commutation. The exact solution neglecting commutation is obtained by using $I_{sc}(t) = I_c/(1 + at)$, and $R_{sc} = atR_s$.

Before making such a comparison, we must first address ourselves to the question of the inductance associated with the shunt resister. Assuming it is made of copper which is initially at room temperature, the ratio of length to crosssectional area is R_s/ρ_{cu}, which equals about $2 \times 10^6 cm^{-1}$. A second constraint to calculate the size comes from the heat dissipation. We assume that the full fault current of 20 KA (RMS) passes through the 3.65 Ω shunt for 3 cycles or about 50 milliseconds. The total energy is almost 10^8 joules. The temperature rise depends on the specific heat and the amount of copper. Assuming an average specific heat of about 0.3 joules/gram K and restricting the temperature rise to 300 K above room temperature, we find a requirement of $10^5 cm^3$ of copper. This equals the product of length and crosssectional area, so together with their ratio calculated above, we find a length of 4.5 kilometers and an area of 0.22 cm^2. If we wind this bifilarly, like the SCFCL, we can keep the inductance small. Making the copper 10 cm wide and 0.4 mm thick, and using the same 0.5 mm insulation as in the SCFCL (the voltages are the same) we find an inductance of 7 μHy.

An additional advantage of the above shunt resistor is a large surface area for cooling. Two additional comments must be made about the temperature excursion. A larger temperature change could be contemplated except for the possibility of multiple faults before the resistor could cool down. Also, however, the resistivity of copper will increase by a factor of two at 600 K, acting as a further limitation of the fault current. Subsequent operations will not dissipate nearly as much heat.

We now return to our calculation of $I_{sc}(t)$ including the effect of finite commutation time. We use a total inductance -- SCFCL (2.5 μHy), shunt resistor (7 μHy) and interconnections (10 μHy) -- of 20 μHy, and set $a = 10^9 sec^{-1}$, which is consistent with an acceptable value of $\tau_p \simeq 4$ μseconds. A comparison of the exact solution, neglecting commutation, with the iterative solution, including commutation is shown in Figure 4-5 where we plot the current through the superconductor in each case as a function of time. We also plot the total power dissipated in the SCFCL, which is $I_{sc}^2 R_{sc}$. Note that even including commutation, the total energy dissipated during switching is a negligible 32 joules.

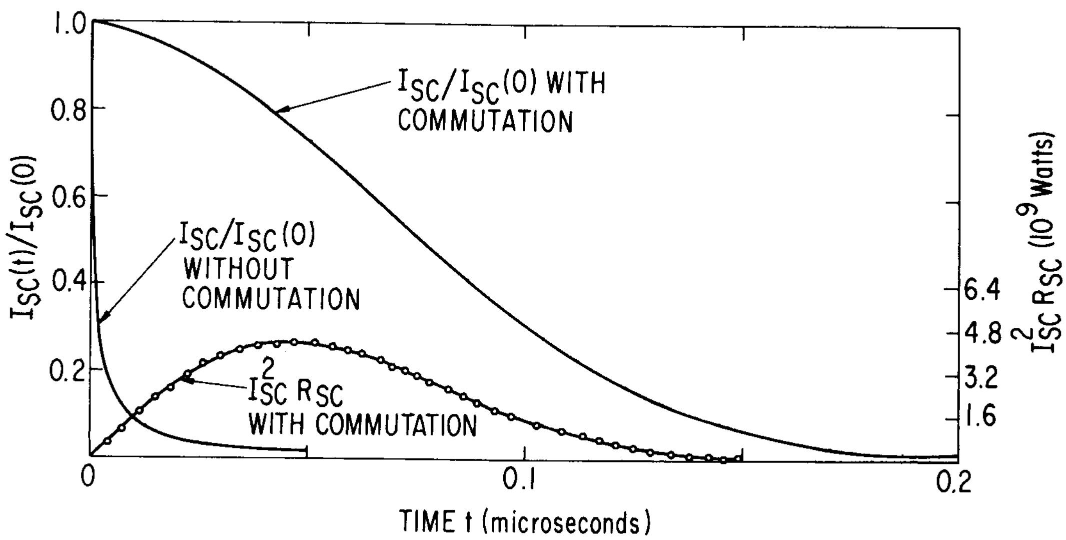

Figure 4-5

The difference is more dramatic for the enthalpy increase in the first part of the superconductor to become resistive. This is shown in Figure 4-6 and compared with the previous hot spot calculation (section 4.3) which ignores the decrease of I_{sc} with time and is clearly an upper limit, no matter what the commutation time or distribution of critical currents. It is clear that neglecting the commutation time will give completely wrong answers. The correct answer probably lies between the model solution including commutation time and the hot spot approximation (which assumes no decrease in I_{sc} with time), because the distribution of J_c will no doubt peak around its average value and be much smaller near its lowest value. We see here, the intimate connection of the commutation time with hot spots. In fact, the problem which is to avoid fusing the conductor during switching must include the effect of commutation time.

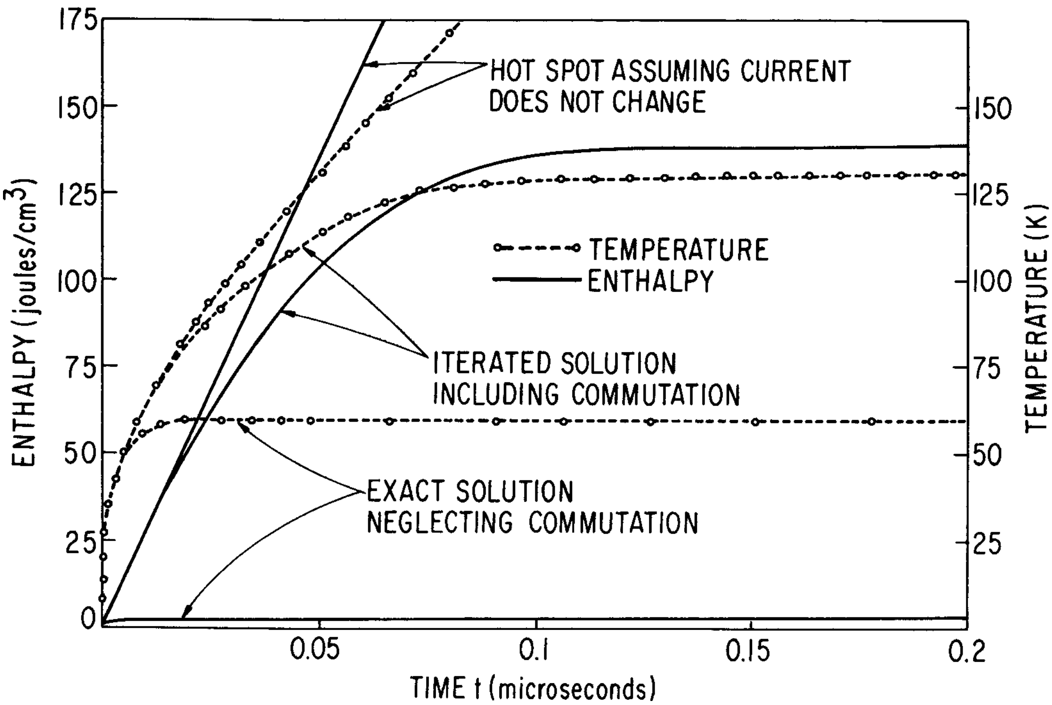

Figure 4-6

To place this criterion on a quantitative basis, we define a time τ_H such that $\rho_N J_c^2 \tau_H$ is the energy density dissipated in the first region to go normal. It is clear that τ_H is approximately the characteristic time for $I_{sc}^2(t)$ to decrease when the commutation time is included. To avoid fusing, we require $\rho_N J_c^2 \tau_H$ to be less than the enthalpy per unit volume at the melting temperature. This requires that $\tau_H < 2$ microseconds for our model system. From the results of Figure 4-5, we find τ_H for our model system to be about 0.06 microseconds leaving room to spare. The maximum temperature rise will be about 125 K (see Figure 4-6). This could be reduced by decreasing the inductances and hence the commutation time, but we do not feel this is necessary.

4.6 A.C. LOSSES

To calculate the expected ac losses during normal operation, we make the usual assumption that the current per width of the film is equivalent to the surface field. Present techniques seem to indicate that 60 Hz losses of 10 μ watts/ cm^2 can be obtained for RMS fields of 700 A/cm. In our case, we have about 300 A/cm which indicates losses of 0.8 μ watts/cm^2 because of the cubic dependence on field. For our surface area this corresponds to 0.32 watts which is much smaller than heat loads into the cryostat (see section 5).

Section 5

CONCEPTUAL DESIGN

In this section we describe a possible design for a working SCFCL incorporating our model of the previous section. As far as possible we indicate the material, fabrication techniques, sizes and shapes, showing as we do that the design is feasible to build. The starting point is the superconducting element for which we describe a modular construction of the entire SCFCL. Finally the cryostats and refrigeration are described.

We have already established the need for thin superconducting films without metallic stabilizers. A possible choice of superconductor is NbN which can be conveniently sputtered. Our model uses 2 micron thick films, 6.7 cm wide and 600 meters long. In section 4, it was found necessary to keep the inductance of the SCFCL very small which implies bifilar winding. This can be simply accomplished by depositing films on both sides of a thin insulating substrate, with the current in opposite directions on either side. The substrate must provide sufficient voltage insulation and preferably be flexible for ease of depositing the superconducting films and fabrication into a SCFCL module. For these reasons mylar appears to be an excellent choice for the substrare. Each module is made from one long ribbon of mylar with the current traveling down one side, crossing over at the end and traveling back up the other side. The thickness will be dictated by the maximum voltage across each module which occurs only for a short period during fault conditions.

The second important consideration is the removal of heat -- transformed into helium gas -- during and after a fault. To accomplish this, a sufficiently large channel of liquid helium must contact each side of the ribbon. The computer program has calculated the helium gas layer thickness, which is generated for each fault on our model system, to be 0.18 mm. Less liquid is consumed because of the volume expansion of 6 in going from liquid to gas at 4 K. Since several faults may occur in a short period of time we require sufficient space for the gas and a sufficient volume of liquid which replaces the gas and cools the superconductor after the fault occurs. Our design allows 3.75 mm of channel for each exposed superconducting surface, which is conservative.

Since the gas bubbles will rise in a gravitational field, we have a means of removing the gas if the films are oriented with their length horizontal and their width (not thickness) vertical. Figure 5-1 shows a possible way to compact the ribbon of a single module such that bubbles rise vertically through the cooling channels. The ribbon is wound spirally out from a 10 cm diameter

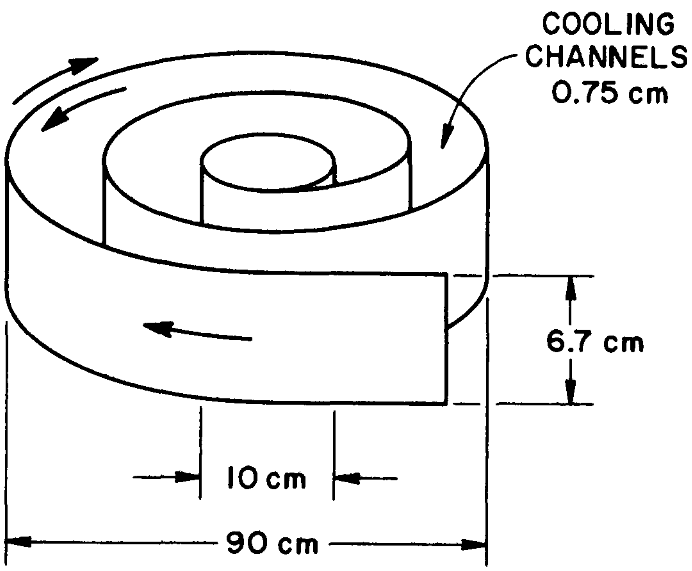

Figure 5-1

hollow drum, on which the conductors on each side of the mylar are connected together. At the outside of the spiral the terminals are connected to other modules on either side.

Using a 7.5 mm space between turns, we place 53 turns out to a diameter of 90 cm. The average radius is 30 cm giving a total length of ribbon in each module of 50 meters. Since the superconductor is on both sides, we need only 6 modules to make the 600 meters total length for our model SCFCL.

The peak voltage of each phase to ground is 118 KV, and that is the maximum voltage across our SCFCL. Hence each of the 6 modules will have a maximum of 20 KV, so the mylar substrate must by 20 mils or 0.5 mm thick (mylar can support about 1 KV/mil).

Figure 5-2 shows how these six modules are stacked into a one meter diameter cryostat, with two high voltage, high current cryogenic feedthroughs. There must be a sufficient resevoir of liquid helium above the highest module to resupply the helium lost from about 20 faults. This corresponds to 22 liters or 2.5 cm depth for our model system. The high voltage leads must be far

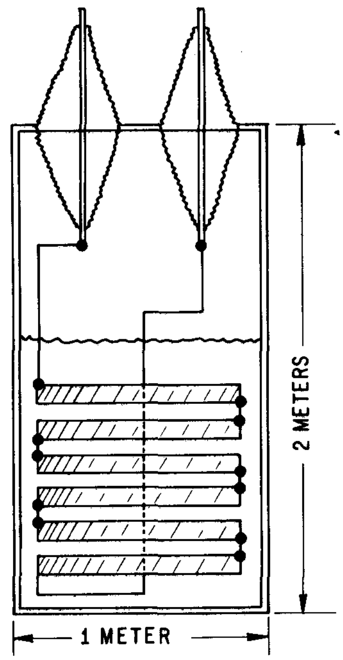

Figure 5-2

enough apart to avoid breakdown in air and in the helium gas in the cryostat. It appears to be marginal as to whether they will both fit easily into a one meter diameter cryostat.

The cryostat is perhaps better made of fiberglass instead of metal to avoid electrical conductors and will be thermally insulated by super insulation to avoid the need for the complication of liquid nitrogen. This may increase the heat loss into the liquid helium but will save considerably on overall operating expenses. The heat losses to the cryostat are dominated by the high current feedthroughs anyway, which consume 5.6 liters/hour for the pair. By comparison the heat leaks into a two meter long and one meter diameter cryostat with superinsulation can be expected to consume 1.7 liters of helium an hour.

A three phase system utilizes three such cryostats and requires a continuous supply of liquid helium. To minimize maintenance and operating costs, it is essential to have a dedicated closed cycle helium liquifier. Since the cost per liter decreases with the size of liquifier, it is more efficient to run all three cryostats from the same liquifier, using insulated transfer lines for distributing the liquid and returning the gas. Between SCFCL's, a spacing of about 10 meters may be required. A storage dewar will help to smooth out fluctuations in demand, or short maintenance outages of the liquifier.

As the final consideration of this section we examine a configuration for a pulsed magnet to provide the trigger action for the SCFCL after a fault. We need a modest field (∿ 300 Oe), but it must be everywhere perpendicular to the superconducting films. This is not trivial for our spiral configuration. The magnet shown in Figure 5-3 consists of two disks inside the cryostat and above and below the six modules. The current is in the sense of a spiral and in

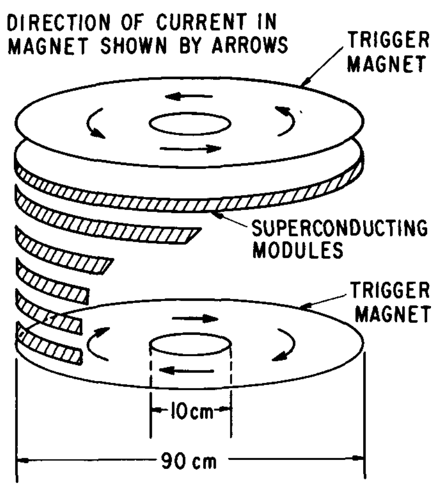

Figure 5-3

opposite directions above and below. This results in a field entering at the sides, leaving in the center at top and bottom, and approximately perpendicular to the superconducting films. The magnet windings could be either superconducting or of a normal metal depending on their relative efficiency. This choice has not been considered here.

Section 6

COST ANALYSIS

In this section we describe our rather detailed analysis of the capital costs and operating expenses for our model SCFCL, along with estimated extrapolations to different values of the appropriate parameters. Each three phase power line requires three SCFCL's with trigger mechanisms, three cryostats with appropriate liquifier and distribution, and three room temperature shunt resistors. In keeping with the work project statement of section 1, we do not include the costs of the shunt resistors or trigger mechanisms.

The materials and fabrication costs are in section 6.1, while the cost of cryostat and refrigeration are considered in section 6.2. The exact fabrication cost is hard to estimate reliably, since long, thin superconducting films are not presently manufactured, although they are considered technically feasible since similar films (aluminized mylar) are manufactured commercially. The costs of the other components are fairly well known, except for the high current, high voltage feed throughs. In the voltage range of our model SCFCL, which incorporates a 145 KV line, feedthroughs have only been constructed for laboratory experiments, generally without regard to minimizing heat losses or costs. In this regard, these heat losses, which do not greatly influence the feedthrough cost, have a large impact on the total cost because of the necessary refrigeration. In section 6.3, we summarize the total cost of the model system of section 4, including extrapolations to other values of the relevant parameters. We conclude this analysis with an estimation of the annual operating costs in section 6.4.

6.1 MATERIALS AND FABRICATION

Of the possible methods for producing long thin films, high rate sputtering (HRS) and chemical vapor deposition (CVD) are the most promising. Both methods seem to be adaptable to making superconducting films on long substrates and at relatively high rates. Because there is presently no commercial source for such films, we only attempt a preliminary fabrication and materials cost estimate.

In the case of CVD, a study at Westinghouse (An Improved Superconductor for Transmission Line Applications, Phase I, A. I. Braginski et al., Westinghouse, USERDA Contract E (11-1)-2522) estimates a fabrication cost of about \$0.64 per micron thickness on an area of one square meter. We can roughly estimate the materials costs, using our tentative choices on NbN for the superconductor and 20 mil mylar for the substrate. For the superconductor we estimate conservatively a cost of $\$20/cm^3$, and for the 20 mil mylar, $\$4/m^2$. Combining these costs we find the total for three phases is

$$C_{F+M}^{CVD} = 3\,\ell w\,(\$4 + \$20\,d),$$

where ℓ and w are given in meters and d is in microns. For our model system this comes to about \$5280.

Similar analysis for high rate sputtering, indicates a greater fabrication cost mainly because of a factor of 10 slower deposition rate and more waste in the targets. We estimate

$$C_{F+M}^{HRS} = 3\,\ell w\,(\$4 + \$40\,d),$$

which comes to \$10,080 for our model system.

Additional fabrication costs of the modules might be about \$10 K, but we do not include in our estimate the cost of installation at the utiliy company, nor the necessary external connections.

6.2 CRYOSTATS AND REFRIGERATION

The refrigeration system, liquifier, storage and distribution, is the major investment cost for a SCFCL. In an attempt to reduce this cost we have compared the costs of running the liquifier continuously (24 hours) to that of running only during off peak hours (12 hours). A 70 liter/hour liquifier costs \$350 K, which includes \$100 K for the extra expander required if the helium gas is not precooled with liquid nitrogen before liquifaction. This machine requires 140 kilowatts of electrical power when operating. At an investment of a capital cost of about $1000 per kilowatt by the electric utility for peak power, this corresponds to an additional $140 K. Running on a 12 hour schedule would require twice the refrigeration size, while avoiding the $140 K peak power cost. It is clear that using the peak power in this case is considerably less expensive. Capital costs of refrigeration are found to be $7000 per liter per hour of liquid helium.

Ancillary equipment, includes liquid helium distribution lines, their controls and helium storage. Based on manufacturer's estimates, the distribution lines (35 meters total) and controls cost $15 K for all three phases and the storage dewars $15 per liter. An empirical result of the computer program dictates one half a liter of storage per meter length of the SCFCL. For the model system we require 300 liters storage at a cost of $4500.

Cryostat manufacturers put the cost of a cylindrical cryostat two meters high and one meter in diameter with a full sized removable flange at the top, at about $17 K. There is a relatively small dependence of the cost of the height of the cryostat, so we assume a constant cost for three cryostats of $50 K.

The cost of the 2000 A, 145 KV feedthroughs is estimated to be $5 K each. This is our own estimate based on commercially available low voltage 2000 A feedthroughs and our extrapolation to high voltages. At even higher voltages, these will no doubt cost considerably more.

The refrigerator capacity needed depends on the static heat loads for the feedthroughs and cryostat insulation, plus a small excess to handle that lost when a fault occurs. High current feedthroughs from American Magnetics dissipate 2.8 liters per hour each for 2000 amps (RMS). Estimates from manufacturers indicate cryostat losses at 1.7 liters per hour each. The helium losses for our model system is 1.1 liters per fault. For an I_c of 4000 amps, the worst case we consider for each phase, is 20 faults per day (see section 2), or 60 faults/day for three phases. This can be replenished in one day at the rate of 2.75 liters/hour. The empirical results of the computer program are the basis for the following approximate expression for the helium loss per fault: $150\ I_c/\rho_N J_c \ell$.

The superconductor material parameters also influence the cost. We estimate an additional cost of \$60 K if J_c is limited to 1×10^6 A/cm^2 instead of our design value of 3×10^6 A/cm^2, making this a fairly important parameter. For ρ_N equal to one half and twice the design value of 300 μΩcm, we find respectively an increase in cost of \$10 K and a decrease of \$20 K. The cost is not as sensitive to ρ_N. As we mentioned in section 4, the operation does not depend on the transition temperature or specific heat, the other material properties of the superconductor.

6.4 OPERATING COSTS

The operation of the helium liquifier, delivering 25 liters per hour consumes approximately 50 kilowatts of power. At the present rate of \$0.03 per kilowatt-hour the cost of running the FCL is about \$13 K per year. Maintenance, primarily associated with the refrigerator, is hard to estimate reliably, but may be 5% of the capital cost, or \$15 K per year.

Section 7

CONCLUSIONS

In this section we summarize our conclusions of earlier sections and indicate the aspects of the problem which should be investigated more thoroughly in future work.

Our primary conclusion of this report is that a SCFCL is indeed technically feasible over a wide range of parameters for the required electrical power source and the material properties of the superconductors available. The economic feasibility will depend ultimately on the value of such a device to the power companies, but the SCFCL must also be competitive in price with alternative types of FCL's. We feel the cost estimate is fairly realistic with the largest unknown, the fabrication of superconducting ribbons of the length required. We find no problems relating to the switching of the superconductor and commutation of current, however, a trigger pulse will be necessary to avoid fusing the line at hot spots.

A fair amount of development work is required, some of which is presently being done in connection with other applied projects in superconductivity. For the most part the technology required for fabrication is already in the hands of commercial companies. Notable exceptions are the high voltage aspect of the feedthroughs and the details of the superconducting ribbon fabrication.

We have extensively studied the design of a SCFCL for a 145 KV (RMS), 2 KA (RMS) three phase line with available fault current of 45 KA (RMS). We have shown that a long superconducting film in parallel with a 3.65 Ω resistor can adequately limit the fault current, in all circumstances, to 20 KA (RMS) and a first loop peak current of 28 KA. Our design requires an isolation switch in series with the superconductor to eliminate excess losses and allow a recovery time of less than 50 milliseconds. Choosing reasonable values of the material properties of the superconductor ρ_N and J_c, we find a compatable solution with a length 600 meters, a width 6.7 cm and a thickness of 2 microns. This can be accommodated in a cryostat which is two cubic meters. The total capital cost of such a device for all three phases is estimated to be just under \$300 K with a yearly operating cost of about \$30 K.

We here list the specific advantages of a SCFCL:

- Solid state switching. There are no moving parts or materials, only the electrons change their state. In other words, nothing wears out.

- Low losses. During normal operation the losses are entirely due to heat leaks into the cryostat and constitute about 0.01% of the transmitted power.

- Fast recovery. The superconducting element is ready for load current within 15 m sec of the fault, i.e., even before the circuit breaker has opened. This could be very useful to quickly restore service to interconnected systems.

- High voltages. There are no particular problems with higher voltages. The element is just longer. High voltage feedthroughs could be quite expensive, however.

Along with these are some disadvantages:

- Low temperature. Dissipation of power at low temperature costs about 450 times as much as room temperature. A closed cycle refrigerator, with possible maintenance is required.

- Sensing. The device is not self sensing.

- Load current. The costs become much greater as the continuous load current is increased. We estimate \$60 K/KA.

In addition, it should be pointed out that the economics of a SCFCL is even more attractive when used in an electrical distribution system already utilizing superconductive or cryogenic equipment (such as generators, transformers or transmission lines). In this case the cost of the high current feedthroughs with necessary refrigeration is entirely eliminated. A savings of roughly half the cost estimated in section 6 would result.

In the following we list the outstanding problems, in the order in which they should be tackled, which is roughly the order of importance.

1. Fabrication of the Superconducting Element. This will involve a program to determine available (and eventually find the optimum) materials which can be deposited on a flexible insulating substrate with high values of ρ_N and J_c and low ac losses. Detailed literature searches would necessarily be followed by an experimental study. Along with this would come a detailed prescription of the fabrication method and cost.

2. Switching the Superconductor. This would involve a detailed study of the switching by an experimental determination of the trigger requirements to keep helium losses low and avoid hot spots. Some computer simulation as in section 4 would also be contemplated. The method of switching, sensing devices, magnet design and estimated losses would be a further extension of this report.

3. Thermal Recovery Time. This would involve an experimental investigatin of the thermal recovery time after a fault. In particular it is important to see how quickly the gas layer is removed so that T drops below T_c.

4. Feedthroughs. Further investigations of high current, high voltage feedthroughs are necessary. It should be stated that this research is already being conducted in other laboratories in connection with other applied superconductivity projects. A very important question here is whether or not a electrically floating metal cryostat can act as one terminal and replace one of the costly feedthroughs.

The most important problem in (1) is the substrate since suitable superconductors are presently available. For this reason, items (2) and (3) could be considered first or concurrently using existing substrates. If research on all these items come to a successful conclusion, the construction of an operating SCFCL prototype can be contemplated.