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SUPERCONDUCTING FAULT CURRENT LIMITER

First Quarterly Technical Progress Report, August 8–November 7, 1978

Work Performed Under Contract No. ET-78-C-01-3015

Gould, Inc.
Spring House, Pennsylvania

U. S. DEPARTMENT OF ENERGY

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First Quarterly Technical Progress Report

August 8, 1978 - November 7, 1978

PREPARED BY

GOULD INC. (I-T-E IMPERIAL CORP.)

PREPARED FOR

DEPARTMENT OF ENERGY
ELECTRICAL ENERGY SYSTEMS

PROJECT MANAGER

Russell Eaton, III

Contributors:

Gould, Inc. Research and Development Division
Spring House and Chalfont, PA

E. M. Spencer, Director, Special Projects
E. B. Khalafalla
D. B. Miller, Project Manager
R. W. Reuther

Gould Laboratory for Electrical and Electronics Research
Rolling Meadows, IL

A. J. Purdes

Gould Information Center
Rolling Meadows, IL

M. W. Casey
M. Laurin

Argonne National Laboratories
Argonne, IL

K. E. Gray

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I. INTRODUCTION, SUMMARY, AND FUTURE WORK

1. INTRODUCTION, SUMMARY, AND FUTURE WORK

The purpose of this project is to investigate the suitability of using a superconducting fault current limiter (SCFCL) in conjunction with other superconducting apparatus or transmission lines. Literature search, consultation, analysis and experimentation are to be carried out to derive a set of operational parameters for a SCFCL and to answer key questions as to the feasibility of a superconducting element to meet these performance objectives.

During the first quarter year of effort, substantial progress has been made on several of these program tasks. A comprehensive search of the literature on SCFCL devices and applications has been initiated; the references which have been obtained to date are evaluated within a framework into which additional references can be added as they are received. It is expected that ten to twenty more sources may be uncovered but that all major topics are already treated by the existing survey.

Consultation with key researchers has occurred to supplement and update the literature search. The information gained during these meetings has been integrated into the literature search (Section 2 of this report.)

The literature search has been divided into three areas: performance objectives (system constraints on SCFCL's), superconducting power apparatus and SCFCL devices. The results of the first two of these

areas have been employed in Section 3 ("Evaluation Criteria") to identify those performance characteristics which a system requires of a SCFCL. These first two areas are again used in Section 4 ("System Analyses") to begin to assign quantitative values to the characteristics set out in Section 3.

Device analyses have also been started in order to determine to what extent the various proposed SCFCL devices meet the requirements of the power system. This effort has not yet generated any reportable results but is scheduled for major emphasis during the second quarter.

During the second quarter then, it is expected that the following tasks will make significant progress: (1) the systems studies to quantify the performance objectives; (2) the device analyses to determine the ability of SCFCL devices to meet system requirements; and (3) more detailed design and analysis of the most promising concept(s) in order to identify key experimental tests which must be performed.

2. LITERATURE SEARCH AND CONSULTATION -

SUPERCONDUCTING FAULT CURRENT LIMITERS

2. LITERATURE SEARCH AND CONSULTATION -

SUPERCONDUCTING FAULT CURRENT LIMITERS

A superconducting fault current limiter (SCFCL) must successfully protect the power system and its components from the harmful effects of fault currents, and it should achieve this function by use of the most applicable superconductivity design concepts. The literature search and consultation with experts has, therefore, been directed toward these two interrelated goals:

1. What performance objectives does the system require of a SCFCL?
2. What is the best superconducting current limiter design concept which meets these required performance objectives?

Several sources were utilized to gather the information contained in this search. Personal and institutional files of the participants from Gould and Argonne were initially reviewed; this constituted a large and current collection since these groups are now and have been actively engaged in fault current limiter design and superconductivity technology. This collection, plus the personal knowledge of the participants, led to further references and to consultation with experts in these fields.

The 1978 Applied Superconductivity Conference was attended since this represented both a source of reports on current technology and a place where many of the experts could be personally interviewed.

Two important consultation visits have been made:

1. Brookhaven National Laboratory, Dr. Eric Forsyth and Staff;
superconducting cable technology, ratings, applications.
2. International Research and Development Co., Ltd.,
T. C. Bartram (interviewed at Annapolis, Md.); superconducting
fault current limiter, technology and applications.

In addition, several key people have been interviewed by telephone,
including:

Naval Research Lab (Cryogenics - I. M. Vitkovitski; Plasma Physics -
Mr. Brown)

M.I.T. - G. A. Oberbeck

EPRI - R. Kennon

Finally, formal, computer-based searches of the international literature
and patents were performed by the Gould Information Center, to insure that
important sources were not overlooked using individual collections and
knowledge. The following specific sources have been searched:

1. Applied Science and Technology Index (1974 - Aug, 1978)
2. Gould Information Center Topic Files
3. Physics/Electrical and Electronic Abstracts
 - o Inspec - File 12/13 searched (1969 - Aug. 1978)
 - o EEA searched (1950 - 1968)
4. Claims - GEM (1970 - Aug. 1978)
 - o U. S. Patents by class and keywords.
5. U. S. Patents (1953 - 1969)
 - o Searched by class

6. World Patent Index (1974 - Aug. 1978)

7. World Patents (1953 - 1973)

o Searched at The Hague.

2.1 PERFORMANCE OBJECTIVES - REFERENCES WHICH DISCUSS THE PROTECTION REQUIRED BY SYSTEM AND COMPONENT CONSTRAINTS.

The "Philadelphia Electric Study" (1.1) is a useful starting point in this survey since it clearly focuses on the issues and requirements from a system point of view. A 10 GW source is to be connected to an urban center by way of a 66 mile transmission link; this is typical of the power levels, transmission paths and load characteristics which will be encountered in the next 10-20 years when the SCFCL would be required. When the transmission is accomplished by three parallel superconducting cables at 230 kV, steady state fault currents are about 135 KA, which is a 5.5X fault or nearly 11X (peak) for a full d.c. offset at the initiation of the fault. The report states that "a breaker that can interrupt 135 KA is viewed with less optimism," and special sequential relaying was used to separate the system under fault conditions so that fault currents were reduced to reasonable breaker capability levels. This radial system also required series capacitors to maintain system stability during a three phase fault when one line was already out for maintenance. Thus, this report clearly shows the sensitivity of the system and its components (in this case, the breakers) to the low impedance of superconducting cables. Current limiters were not considered.

Dodds, et al (1.2) provide a good discussion of the concepts involved in analyzing and evaluating fault current limiters (FCL), in terms of the FCL parameters to meet system requirements. The attached "Table 0-1" from this report also is useful in establishing the general magnitudes of continuous current, short circuit fault current

TABLE 0-1
CURRENT RATINGS
FAULT-CURRENT LIMITER

Voltage Class kV	Continuous Current A rms	FAULT CURRENT			DEVICE LOCATION
		Let	Through	Available kA, rms	
		Sym rms kA	Peak Mom. kA		
15	600 to 4000	1 to 6	15	20	A
	1200	10	35	20 to 45	B
23	600 to 2000	1 to 6	15	20	A
	1200	10	35	20 to 45	B
38	600 to 3000	1 to 6	15	15 to 20	A
	1200	15	35	20 to 45	B
46	600 to 3000	1 to 6	15	15 to 20	A
	1200	15	30	20 to 40	B
72.5	1200 to 3000	1 to 6	15	12 to 20	A
	1200 to 3000	15	30	20 to 35	B
121	1200 to 3000	1 to 6	20	12 to 20	A
	1200 to 2000	20	35	25 to 40	B
145	1200 to 3000	1 to 6	15	15 to 20	A
	1200 to 2000	20	35	30 to 45	B
169	1200 to 3000	1 to 6	15	15 to 30	A
	1200 to 2000	15	30	30 to 60	B
242	1200 to 3500	1 to 6	20	15 to 35	A
	1200 to 2000	20	40	25 to 80	B
362	2000 to 3000	1 to 6	30	20 to 40	A
	2000 to 3000	35	65	40 to 60	B
550	2000 to 3000	1 to 6	30	20 to 30	A
	2000 to 3000	35	65	40 to 60	B

DEVICE LOCATION CODE:

A - Transformer, Sectionalizer, or High-Capacity Line

B - Feeder or Line

Source: Ref. 1.2

("available current") and the value to which the current should be limited ("let through") in order to protect the system.

Hartmann and Wohlgemuth (1.3) have made a more recent evaluation of the short circuit ("available") fault currents which might be encountered in various sites in the Northwest if superconducting cables were to be employed. The results are included here (their "Table III"). The worst case (Grand Coulee with full d-c offset) had fault current of 9.4X rated current, and so might "be a candidate" for a FCL.

Another conceptual system study, performed by Brookhaven National Laboratory and Long Island Light Company personnel (1.4), also used superconducting cable. The power level was 4800 MW (2 circuits), the voltage, 345 kV, and the length, 43 miles. For 4.0 KA normal (continuous) current, the highest fault current was 15.4 KA; this would suggest a first half-cycle peak of about 42 KA (15.4×2.7 ; ANSI C37.06) or about 7X the continuous peak current.

Evans and Rothenbuhler (1.5) indicate two specific instances where FCLs may be required on the Southern California Edison Company system. In both cases, added parallel transformers (to serve additional load) will raise the fault current above the existing breaker ratings. Solutions are to sectionalize the system so fault currents will be reduced to breaker capabilities (as in the Philadelphia study), to replace the breakers or to use FCL's.

Blinkov (1.6) states that short circuit currents in superconducting cables may be 3 to 10 times the continuous level and will last for

TABLE III
System Fault Capacity (1980 Expected) and Fault
Currents as Multiples of Rated Cable Current for
Various Superconducting A-C Cable Sizes

Voltage (kV)	Location	Fault Capacity* (MVA)	Cable Capacity (GVA) Cable Rating (X rated cable current)		
			8	6	4
500	G.Coulee	28,000	3.5	4.7	-
	NPR	25,250	3.2	4.2	-
	John Day	23,000	2.9	3.8	-
	Ch. Joseph	20,750	2.6	3.5	-
	Lo. Mo.	19,000	2.4	3.2	-
	L. Go.	17,200	-	2.9	-
			6	4	2
230	G.Coulee	20,750	3.5	5.2	-
	Big E.	15,700	2.6	3.9	-
	Wanapun	14,800	2.5	3.7	-
	Ch. Joseph	14,400	2.4	3.6	-
	R. R.	13,750	2.3	3.4	-
	Trojan	10,000	1.7	2.5	-
			1.6	2.3	-
			2		
115	Harborton	5,000	-	-	2.5
	R. Is.	4,400	-	-	2.2
	McNary	4,400	-	-	2.2
	Big E.	4,100	-	-	2.
	Ice Hbr.	2,300	-	-	1.2
	G.Coulee	2,200	-	-	1.1
	Bonn	2,100	-	-	1.

SOURCE: REF. 1.3

0.1 to 1.0 seconds. Either overcurrent capability of this sort must be built into the cable or a FCL will be required to prevent a "flux jump" and loss of superconductivity.

On a consulting visit to Brookhaven National Laboratory (1.7), reference was made to a publication (1.8) which cited fault currents even as high as 25X normal. The high fault currents and the need to protect the external system, particularly the circuit breakers, were emphasized during this visit.

If the SCFCL is of the type which needs a trigger signal to switch from a normal mode to a limiting condition, then the fault sensing and relaying schemes also become important system considerations. Gallen (1.9) has reviewed this aspect of FCLs, and he makes the following comments: The relay pick-up setting should be no more than half the value to which the current will be limited, some relaying schemes (e.g., phase sensitive types) may be affected by the FCL in the circuit, the FCL is beneficial in reducing CT saturation, and finally short circuit calculations with the FCL in the circuit should be made to evaluate adequacy of relaying schemes and to determine relaying settings. Dodds (1.2) indicates that measurement of di/dt is the fastest means of detecting a fault. Lee and associates report on an ultra-fast fault sensor based on the di/dt principal for use with fault current limiters (1.10). The demands which a system makes on a SCFCL must finally be stated as a set of specific, rigorously defined ratings or performance objectives before one can judge whether a particular SCFCL device meets the required design objectives. Such a set of ratings also defines

the tests which must be designed and carried out to show that the device is suitable. Dodds (1.11) has provided a list of ratings which must be specified; these are reproduced on the following page (his Table I) along with two example sets of numerical values for these parameters.

TABLE I. Ratings

	RP 281-1	RP 281-2
1. Rated Maximum System Voltage	72.5kV rms	72.5kV rms
2. Rated Continuous Current	3000 A rms	2000 A rms
3. Available Short Circuit Current	35kA rms	6350 A rms
4. Limited Short Circuit Current	17.5kA rms	3400 A rms
5. Available Major Loop Peak Asymmetrical Current	94.5kA peak	17145 A peak
6. Limited Major Loop Peak Asymmetrical Current	47.3kA peak	9180 A peak
7. Three Second, Short Time Current Carrying Capability	3750 A rms	12700 A rms
8. Close and Latch Capability	6000 A rms	20320 A rms
9. Low Frequency Withstand Voltage to Ground	160kV rms	160kV rms
10. BIL to Ground	350kV peak	350kV peak
11. Duty Cycle	3 x 5 cycle operation	3 x 15 cycle operations
12. Number of Operations	20	20
13. Reset Time	20 cycles	20 cycles
14. Sensing Discrimination Level	17.5kA rms	3400 A rms

Source: Ref. 1.11

BIBLIOGRAPHY; SECTION 2.1, PERFORMANCE OBJECTIVES

- 1.1 Philadelphia Electric Co., "Evaluation of Economic and Technical Viability of Various Underground Transmission Systems for Long Feed," U.S. DOE/EES HCP/T-2055/1, Dec. 1977.
- 1.2 T. H. Dodds, et al (I-T-E Imperial/Gould), "Development of Fault Current Limiters for Electric Power Systems," EPRI Final Report TD-130, March 1976.
- 1.3 D. P. Hartmann, D. G. Wohlgemuth (BPA), "Power System Short Circuit Planning for Superconducting Power Transmission," IEEE Trans. MAG-13, 149-153, Jan. 1977.
- 1.4 E. B. Forsyth, G. A. Mulligan, J. W. Beck, J. A. Williams, (BNL, LILCO, PTI), "The Technical and Economic Feasibility of Superconducting Power Transmission; A "Case Study," IEEE PES Summer Meeting, Anaheim, July, 1974.
- 1.5 M. L. Evans, W. N. Rothenbuhler (So. Calif. Edison) "Planning for Fault Current Limiters on Electric Power Systems," Symposium Proceedings: New Concepts in Fault Current Limiters and Power Circuit Breakers, EPRI EL-276-SR, Buffalo, Sept. 28-30, 1976.

- 1.6 Y. L. Blinkov, "An Analysis of the Operating Conditions of Superconducting Power Transmission Lines," IEEE Trans MAG-13, 144-148, Jan. 1977.
- 1.7 Consultation: Brookhaven National Laboratory, Dr. E. B. Forsyth and Dr. G. H. Morgan on October 13, 1978.
- 1.8 J. Sutton, Tech. Disclosure Bulletin, No. 232, August 1974 CERL.
- 1.9 T. F. Gallen (Phila. Electric Co.), "Protective Relaying Implications of FCL's" Buffalo Symposium - New Concepts, EPRI EL-276-SR, Sept. 28-30, 1976.
- 1.10 I. Lee, et al, "An Ultrafast Fault Sensor for a Fault Current Limiting Device," IEEE/PES Summer Power Meeting, Los Angeles, July 1978, F-78-737-9.
- 1.11 T. H. Dodds, (I-T-E Imperial/Gould), "Ratings & Performance Specifications for Fault Current Limiters," Symposium - New Concepts, Buffalo, EPRI EL-276-SR, Sept. 28-30, 1976.

2.2 SUPERCONDUCTING POWER SYSTEM COMPONENTS

When the phenomenon of superconductivity is applied to power system components, the impedance of the device is often lower, or in the case of generation, the impedance of the transformer may be eliminated, so that the fault currents will be higher than with conventional devices. The need for fault current limiters in future power systems may, therefore, depend on characteristics of these devices.

The need for superconducting fault current limiters is predicated even more strongly on the presence of other superconducting components since it is possible that SCFCL's can only be economically competitive when they share refrigeration with another component which must already be present.

In this section, therefore, references on superconducting components, specifically generators, transmission lines, transformers and energy storage coils, are evaluated both to obtain specifications for FCL system studies and to point out what components might reasonably be able to share refrigeration with the SCFCL.

SUPERCONDUCTING GENERATORS

J. S. Edmonds, of DOE, estimates that an additional 48 GWE of generation must be installed by 2000 (2.1). The per unit size of conventional generators has reached its upper limit of about 1200MVA, but superconducting generators are projected to be capable of achieving much larger size 3000 MVA by one account (2.1) and as high as 11 GVA by another (2.2). As a result, superconducting machines are predicted to constitute possibly as much as 75% of the new generation addition (2.1)

Superconducting generators have two important features which may require the use of FCL's in systems using these generators. The first feature is the high voltage capability of these generators (2.1, 2.3, 2.4). A design goal is to be able to connect them directly to the transmission lines, thereby eliminating the cost of a transformer. Such an arrangement would also eliminate the current-limiting reactance of the transformer, and short circuit currents can, therefore, be predictably higher unless a fault current limiter is purposely added.

The second important feature of the superconducting generators is the low reactance of these machines compared with conventional alternatives (2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 2.10).

The following Table shows rated values for conventional and superconducting turboalternators:

<u>MVA</u>	<u>KV</u>	<u>X_d</u> <u>(p.u.)</u>	<u>X'_d</u> <u>(p.u.)</u>	<u>X''_d</u> <u>(p.u.)</u>	<u>H</u> <u>kW-sec/KVA</u>	<u>s/c</u> <u>Conv.</u>	<u>Reference</u>
3	1.38	x	.26	.22	x	s/c	2.8
5	4.16	x	.21	.14	x	s/c	2.5
x	x	.5	.3	.25	3.0	s/c	2.6
x	x	.95-1.45	.12-.28	.07-.17	4-8	Conv.	2.13
300	20	.272	.199	.110	2.52	s/c	2.12
1000	x	.38	.25	.1	2.42	s/c	2.7
1075	x	1.73	.210	.155	2.81	Conv.	2.9
1200	x	.52	.29	.16	x	s/c	2.2
1200	x	1.8	.32	.26	x	Conv.	2.2
1200	30	.267	.197	.109	x	s/c	2.9
1200	30	.276	.20	.20	2.34	s/c	2.12
1200	x	.514	.400	.240	1.86	s/c	2.9
2000	x	.5-.6	.3-.4	.2-.25	x	s/c	2.11
2000	x	.54	.40	.32	4	s/c	2.10

x = not given

These lower reactances will lead to higher short-circuit currents which can damage the generator itself (21, 24, 28, 32) and auxiliary equipment (e.g., circuit breakers) designed to protect the generator. Serious attention should be given to the degree to which superconducting fault current limiters (possibly built as an integral part of the machine) could improve the superconducting generator short-circuit design problem.

When considering FCL's for use with machines, a possible stability problem should not be overlooked. Ordinarily, one would think that the low subtransient impedance of the superconducting machines would improve the stability limits of the system. As it turns out, the critical clearing time is about the same or perhaps only slightly better than conventional machines because the lower reactance is offset by the lower inertia constant of the superconducting machines (21, 23, 17, 24, 28, 30, 33, 32). Adding a FCL would then raise the impedance further, thereby possibly shortening the critical clearing time. System analyses should be carried out to evaluate the importance of this situation.

SUPERCONDUCTING POWER TRANSMISSION CABLES

Returning to the "Philadelphia Electric Study" (1.1), we see a good illustration of the future need for high capacity underground cables. Urban loads will require increasingly larger supplies of electric power over ever enlarging urban areas. The increasing cost of the lengthening transmission paths through these urban areas, along with the public opposition to the visual effects of overhead transmission lines, will favor narrow right-of-way cables rather than overhead lines with their wide land corridors (2.20).

The amount of power which a conventional cable can carry is limited by the heating due to electrical losses in the conductors and dielectric material. Some values are shown in "Table IV," taken from Hartmann and Wohlgemuth (1.3). If the conductor in the cable is superconducting, then the losses and heating diminish considerably and the cable can transmit much more power. A-c superconducting cable should, in fact, be capable of carrying nearly its full surge impedance loading (2.14).

Superconducting cables may be operated either a-c or d-c. The d-c cable has the advantages of no a-c losses in the dielectric or superconductor and no a-c capacitive current. The d-c cable must, however, have expensive terminal equipment to convert the power between a-c and d-c, and so there is a power/distance combination below which the a-c cable is more economically attractive. Keller (2.15) estimates this crossover point to be at about 5-10 GW and 100 miles, without considering any

TABLE V

Performance Capabilities of Fully Compensated 345 kV 2000 MCM Paper-
Insulated Oil-Pipe-Type Cable System

Summer Thermal Rated Capability 1440 MVA (100 Percent Load Factor)

<u>Locations of Compensating Reactors</u>	<u>Maximum Permissible Power Delivered to Unity Power Factor Load at</u>			
	<u>16 Km</u>	<u>32 Km</u>	<u>64 Km</u>	<u>160 Km</u>
With reactors at each terminal only	430 mw	405 mw	278 mw	0 mw
(Reactor size at each terminal)	(85mvar)	(170mvar)	(340mvar)	—
With reactor at each 1/4 point of total line length	440 mw	435 mw	430 mw	385 mw
(Reactor size at each terminal)	(21.25mvar)	(42.5mvar)	(85mvar)	(212.5mvar)
(reactor size at intermediate points)	(42.5mvar)	(85mvar)	(170mvar)	(425mvar)
With reactor at each 1/6 point of total line length	—	—	430 mw	416 mw
(Reactor size at each terminal)	—	—	(56.67mvar)	(141.67mvar)
(Reactor size at intermediate points)	—	—	(113.35mvar)	(283.33mvar)
With reactor at each 1/12 point of total line length	—	—	—	435 mw
(Reactor size at each terminal)	—	—	—	(70.83mvar)
(Reactor size at intermediate points)	—	—	—	(141.67mvar)
Total reactor requirements - mvar	170	340	680	1700

Source: Hartmann & Wohlgemuth (1.3)

additional stability and control benefits which would accrue from the d-c (asynchronous) intertie.

The ability of a cable to sustain a fault is measured by the amperes per unit width of conductor (which is really a measure of the magnetic intensity vector, $\vec{H}$, at the surface of the conductor.) Keller (2.15) states that d-c cable can be operated as high as 2500 A/cm, while the a-c cable should be kept below 500 A/cm.

Garber describes an a-c cable being developed at Brookhaven National Laboratory (2.16). This is a 138 kV, 4KA design which would normally operate at about 500 A/cm. During a consultation visit (1.7), the present BNL design was reported to be 300 A/cm operational, 400 A/cm continuous overload. The transition to the normal state (using Nb_3Sn) is at about 2700 A/cm (at 6.7°), or at 5.4X normal. In the BNL study cited above in Section 2.1, Reference (1.4), the current density during the 15.4 kA (7X) fault was 1408 A/cm; with a full d-c offset, this would be about 3800 A/cm on the first half cycle. Thus, it would appear possible that a FCL could occasionally be of use in maintaining continuity of cable service. The BNL personnel believe that inclusion of a FCL might improve service slightly but would not be a factor in changing the cable design for reduced cost (1.7).

The controlling factor in superconducting cable design is the required operating voltage rather than the current specification (1.7). The inner conductor diameter must be sized to meet dielectric stress limitations; this generally provides ample space for superconductor to carry the

required current. Design stress is 10MV/m, which is about half the corona inception level.

Some further a-c superconducting cable characteristics can be obtained from a paper by Rogers, Slaughter and Swift (2.17). This is a 33 kV, 750 MVA, 13 KA design which has to sustain a 91 KA, 1s fault (7X fault). Niobium was chosen for the superconductor. The "mean" stress was 20 MV/m. With high purity aluminum backing, and a maximum temperature limit of 20° K the maximum fault current density was calculated to be 2.52×10^5 A/m; the normal working current density, one-seventh this value, then becomes 3.6×10^4 A/m.

D-c superconducting cable parameters can be determined from the publications of the Los Alamos group (2.18, 2.19). Parameters for 100, 200, and 300 kV cables are shown in "Table I" taken from Reference (2.19). The LASL d-c cable employs Nb₃Sn superconductors. Note that the maximum electrical stresses are 10-20 MV/m, and that the rated linear current density in all three cases is 2361 A/cm, which is in keeping with Keller's guideline of 2500 A/cm for d-c cable (2.15).

Control of d-c cable fault currents are discussed in References (2.18) and (2.19). Maximum fault current is calculated to be about 1.7 pu on the 300 kV cable. This assumes that the current is limited by blocking the third thyristor valve after the fault occurs. Generally, the current could be limited by blocking the first valve. D-c breakers would be useful in controlling fault currents if these breakers could be made to operate in less than 10 ms (2.19). No discussion has been found regarding use of a FCL with the d-c superconducting cable.

TABLE I

Parameters of Three DC SPTL's

Design	A	B	C
Rated Power, GW	2.5	5.0	7.5
Rated Voltage, kV	100.	200.	300.
Rated Current, kA	25.	25.	25.
Current Density, A/mm ² in superconductor	15000.	15000.	15000.
overall	90.	90.	90.
Max. Electrical Stress, kV/mm	10.	15.	20.
Inductance, nH/m	119.	158.	178.
Capacitance, pF/m	234.	175.	156.
Surge Impedance, Ω	22.5	30.1	33.8
Diam of Central Channel, mm	25.	25.	25.
ID of Dielectric, mm	33.7	33.7	33.7
OD of Dielectric, mm	61.0	74.3	82.1
OD of Cable, mm	73.4	87.7	96.0
ID of Enclosure, mm	82.7	96.1	103.8
OD of Enclosure, mm	248.	288.	312.
No. of Subcables			
Inner Conductor	20.	20.	20.
Outer Conductor	90.	90.	90.

Source: Chowdhuri and Laquer (2.19)

TRANSFORMERS AND ENERGY STORAGE COILS

Superconducting transformers (2.21, 2.22) and superconducting energy storage coils (2.23, 2.25) have also been considered for use in electric power systems. The transformer has the important features of much reduced size and higher efficiency than conventional units of the same voltage and KVA ratings. It is recognized, however, that a large through fault could cause the transformer windings to convert to normal resistivity with damaging loss. The windings (Nb_3Sn) are designed to operate normally at 400 A/cm and could operate up to 2600 A/cm (rms), or up to a 6X or 7X fault. The leakage reactance of s/c transformers is also low (e.g., 6%) so "external reactances" may be required to limit fault current (2.21). Fault current limiters may also be required to protect the external circuit components, such as circuit breakers, used with these transformers.

Large superconducting coils are planned for use in improving the load factor of electric power systems (2.23). Large coils are also being developed to drive future fusion power reactors. The worst condition for a large inductor is a fault at one terminal; the voltage across the last turn at the other terminal can increase to 30X normal, and the current to 60X normal (2.24). A SCFCL might be built as an integral part of such a coil to protect the coil and neighboring hardware and personnel.

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2.3 TYPES OF SUPERCONDUCTING FAULT CURRENT LIMITERS

All proposed SCFCL's fall into one of the following four classes.

- (1) Variable resistors
- (2) Variable resistor/inductor combinations
- (3) Variable saturation iron inductors
- (4) Variable shielded iron inductors

The physical phenomena required to accomplish the above actions include the following.

- (1) Driving a conductor element from the SC to resistive state by use of heat, current or magnetic field.
- (2) Destroying the magnetic shielding ability (Meissner Effect) of a SC by an increase in magnetic field.
- (3) Reducing the magnetic shielding ability of iron by driving it into saturation.
- (4) Reducing the permeability of iron by saturation with a SC coil.
- (5) Driving iron out of saturation with a fault current.

The differences between articles and patents relating to a particular type of SCFCL are their emphasis on certain aspects of device operation and means for improving this operation.

ABSTRACTS OF SCFCL REFERENCES

VARIABLE RESISTORS

- 3.1 * Garwin R. L., Multi-Layered Cryogenic Switching Device

and

- 3.2 Nyberg J. J., Superconducting Switching Elements

Coaxial arrangements are described having the current limiter as the outer conductor and bias and trigger circuits as inner conductors. By suitable choice of bias current, the trigger current required to drive the limiting conductor into the resistive state can be made independent of the current normally flowing in the current limiting conductor. Also, application of a suitable bias current allows unidirectional current flow to be achieved.

A nonresistive scheme is also described which controls the mutual inductance between input and output coils. A shorted SC control coil interposed between input and output acts to prevent the flow of flux between the two coils. A means is provided for driving the control coil into the resistive state. Magnetic flux is now able to flow directly between input and output, resulting in the transfer of power.

* See reference sources in the bibliography at the end of this section.

3.3 Lee E. S., Wire Wound Cryogenic Device

A current flowing in a coil wound around a SC gate conductor applies a nonuniform magnetic field along the length of the gate conductor. This is accomplished, for example, by varying the pitch of the coil. As the current in the coil is increased, a greater fraction of the gate conductor is driven into the resistive state. It is possible by this means to vary the resistance of the gate conductor in a continuous fashion by adjustment of the current in the coil.

3.4 Mawardi O. K., Cryogenic Switching Systems for Power Transmission Lines

A switch is described which has a coaxial feedthrough into a cryostat housing the switch. The coaxial geometry of the switch is preserved inside the cryostat and consists of a straight inner conductor and a thin SC outer cylinder. Switching of this outer conductor is accomplished by the magnetic field from the inner conductor. Alternatively, an external coil is provided to switch the SC at an arbitrary current level in the switch itself.

3.5 Massar E. and Voigt H., Superconductive Switching Path for Heavy Current

A magnetic shield of SC material is positioned in the vicinity of a SC winding having current flowing therein. When the shield is in the SC condition, the magnetic lines of force produced by the winding are forced into a longer path than without the shield. When the current in the winding reaches a predetermined intensity, the shield is driven normal and the magnetic field increases within the winding to a magnitude above the highest critical magnetic field intensity at any point in the winding.

The rapid switching of the entire length of the winding ensures that hot spots leading to switch destruction do not develop.

3.6 Kafka W., Switching Device for Disconnecting Cables

The SC switch is driven into the resistive state by exceeding its critical current density. The switch consists of at least two SC conductors connected in parallel. When the high resistance state is desired, a switch is opened to disconnect one of the parallel conductors from the circuit. Current is commutated into the second conductor, increasing its current density above the critical value and driving it into the resistive state. A switch disconnects this conductor from the circuit, commutating current into a parallel room temperature resistor.

3.7 McConnell L. D., Cryogenic Current Limiting Switching

A SC element is placed in the center of a normal metal cylinder which carries current during continuous operation. To switch the limiter, a mechanical breaker simultaneously inserts the SC element and removes the normal metal cylinder from the circuit. The current which is commutated into the SC drives the SC into the resistive state to limit the current.

A second embodiment of the invention uses a SC and non-linear resistor in parallel, with the SC carrying continuous load current. When the critical current of the SC is exceeded, current is commutated into the resistor which self-heats to limit the current.

3.8 Croso H., Switch for Superconducting Circuit

A device is described which minimizes the mutual inductance between the current limiting SC and a magnetic switching coil. The object is to eliminate the voltage which is induced in the SC when the magnetic switching coil is energized. The SC is arranged in layers of adjacent turns so as to form a toroid. This toroid is surrounded by an external switching winding, the consecutive turns of which extend in planes substantially at right angles to the planes of the SC winding. By various winding techniques, the inductance, and thus the time constant, of the magnetic switch is also reduced.

3.9 Harrowell R. V., A New Superconducting Switch

A SC switch element is conceived which consists of a SC bonded to a semiconductor backing. The purpose of this construction is to prevent hot spots in the SC from destroying the switch. As a hot spot develops the semiconductor in contact with the SC lowers its resistance and commutates the current. The crucial requirement of the semiconductor is that it should have, just below its melting point, the correct intrinsic resistivity, for which an expression is derived.

3.10 Lindsay J. D. G., Development of a Superconducting Switch for Magnetic Energy Storage Systems

The construction and testing of a SC switch constructed of Nb-Ti multifilament wire is detailed. Triggering of the switch is accomplished by discharging a capacitor bank through the SC. Switching times of from 2 to 10 microseconds were attained. Recovery time of the switch was 600 seconds.

3.11 Grawatsch K. et al, Investigations for the Development of Superconducting Power Switches

Superconducting switches were constructed from NbTi foil, NbTi wire and NbN sputtered sheet. Thermal, magnetic and current triggering were investigated. It was concluded that current induced switching was the best method for fast switching in the range of 10 μ sec. The behavior of the switched materials in the "opened phase" could be quantitatively described by the heat conduction in the material and the heat exchange with the surroundings. This relation has to be considered for switches which are not eventually opened with a series mechanical switch.

3.12 Weinmiller J., Superconductive Switch

A switch is described which allows for rapid thermal recovery between switching operations. A SC tape is bifilar wound in the form of a cylinder, the layers of conductor being separated by permeable strips of fiberglass cloth. The resultant intimate contrast between SC and helium coolant allows rapid recovery of the SC state. Triggering of the switch is accomplished with a torodial winding which is wrapped around the cylindrical layers of SC material.

3.13 Massar E., Current Limiter with Superconductive Coil

A current limiting SC device is described which can be switched by its own magnetic field. SC magnetic screens are arranged between the two halves of the current limiting winding. During continuous operation, magnetic lines of flux produced by the winding current are forced into a longer path than without such screens. Increase of coil current above a certain value will destroy the shielding ability of the screens, resulting in a sudden increase of the magnetic field applied to the current limiting winding.

This magnetic field will be sufficient to drive the winding into the resistive state, thus limiting the current. An additional feature of the present design is the incorporation of a means for driving a large current through the shield. This allows the switch to be triggered at different levels of current in the main circuit.

3.14 Massar E., Superconductive Switch for Heavy Current

A switch conductor is combined which consists of niobium bonded to a plastic carrier. The thickness of the carrier is chosen to give the desired short switching time. Minimizing the time required to switch into the resistive state reduces the chance of hot spots destroying the switch. A compromise must be made between having a short switching time and a short recovery time.

3.15 Gerlach H., Arrangement for the Control of a Superconductive Element

A triggering mechanism is described which applies power to a heater in intimate contact with a SC element and drives it into the resistive state. The heater circuit is connected in series with the oppositely wound secondaries of two transformers. The primaries of these two transformers are in series with the SC switch element. During continuous operation, no current flows in the heater circuit.

Upon increase of the current in the primary circuit, the cores of one of the transformers saturates. Current now flows in the heater circuit, driving the SC element into the resistive state. An alternate scheme is described which uses one saturable and one nonsaturable choke to control power to the heater.

3.16 Gray K. E. and Fowler D. E., Superconducting Fault Current Limiter

The technical analysis of a thin film resistive current limiter was performed. A circuit having 145 kV, 2000A continuous operation and an available fault current of 45 kA was assumed. It was concluded that driving the SC film into the lossy state with an external magnetic field was the most promising method of avoiding hotspots during switching into the resistive state. Upon switching the SC, current would be commutated into a room temperature resistor. A major cost of this design is high current/high voltage cryostat feedthroughs; this would be less of a problem if the limiter were used in conjunction with a SC cable.

3.17 Dodds T. H. et al, Development of Fault Current Limiters for Electric Power Systems

Cost estimates for the current limiter design described in 3.16 are presented. The necessity of using a shunt resistor to reduce helium boiloff during a fault is discussed and helium costs/year are estimated for several resistive limiter/shunt resistor ratios. It was concluded that this limiter would be economically competitive for voltage levels above 550 kV.

3.18 Massar E., Current Limiting Device for an Electrical Network

The primary winding of an air core transformer is placed in series with the network to be protected and the secondary winding connected in series with a SC element. An iron enclosure is used to shield the SC from the transformer leakage flux.

When the current limiting action is desired, the iron shield is driven to saturation by means of a magnetizing coil. The transformer leakage flux enters the iron enclosure, driving the SC into the resistive state and providing current limiting action.

This design reduces the high voltage requirements of the SC section.

3.19 Muller K., Superconducting Current-Limiting Device for

Alternating Current

The costs and capabilities of SC current limiters are compared with transformer and resonance coupling types. Support equipment required for a resistive SCFCL is outlined. The use of a high current pulse to trigger the SC/resistive transition is reviewed in detail. Both ohmic and induction-type (resistive/inductive) devices are discussed and design equations presented. The results of small scale device tests are outlined. It is concluded from these tests that a SCFCL would be useful in utility power networks.

VARIABLE RESISTOR/INDUCTOR COMBINATIONS

3.20 Massar E., Current Limiting Device

A device is conceived which consists of two parallel connected and inductively interlinked inductive windings which have substantially equal, but mutually opposite ampere turns. One or both of the windings are made of SC material. During continuous operation, the device has substantially zero inductance and resistance.

When a critical current occurs, one of the coils becomes resistive, greatly reducing its effective ampere turns. The current is now limited by the other winding whose inductance is fully effective. Mounting the switching winding within the current limiting inductive winding promotes the SC/resistive transition by exposure to the magnetic field of outer winding.

3.21 Massar E., Current Limiting Device for Limiting Short-Circuit

Current in Energy Transfer Systems

This concept is an extension of that described in Ref. 3.20.

In this previous resistive/inductive device, the SC switching winding and the current limiting inductor are concentric. This arrangement results in near compensation of magnetic flux in the two windings. Stray uncompensated flux causes a residual reactance during continuous operation.

To allow large currents to flow through the limiter without switching the SC winding, it is necessary that the voltage drops across the two opposed winding be equal. This can be accomplished by placing an external inductor in series with the SC winding.

3.22 Cronin J. C., Fault Current Limiter Using Superconductive Element

Normal and SC coils are wound in opposition on an iron core. The effective impedance of the device is related only to the resistance of the winding of the normal material. Upon switching the SC to the resistive state, the device will have an impedance related to the inductive reactance of one of the coils.

A second device consists of a transformer which has a primary winding in series with the main circuit and a secondary winding having a SC element connected there across. During continuous operation, the SC acts as a short so that the impedance seen at the primary winding is very low.

When the current in the primary reaches a given value, the secondary current also reach a value sufficient to switch the SC element. The effective primary impedance is then equal to the product of the square of the ratio of primary to secondary turns and the resistance in the secondary. This technique allows a reduction of the required length of the SC element.

3.23 Oberbeck G. A., Saturable Reactor Current Limiter

A device is conceived having coils wound on a three legged iron core. One of the legs has a DC bias winding for driving the other two legs into magnetic saturation. Series opposed coils, wound on these saturated legs, are in the power circuit to be protected. When the current in the power circuit increases above a certain value, one of the iron cores is driven out of saturation. The large inductance thus introduced into the circuit limits the current.

The biasing magneto-motive force may arise from permanent magnets, normal DC current or DC superconducting current. A small scale device using a permanent magnet was built and tested to demonstrate the operating principles.

3.24 Parton, K. C., A New Power System Fault Limiter

A current limiter for power systems is described which utilizes the principle of driving an iron core out of saturation. One winding on the iron core is in series with the power circuit. A second SC winding biases the iron core into saturation, resulting in a low inductance during continuous operation.

When an overcurrent drives the iron out of saturation, an inductance is introduced which limits the current. To protect against over-currents of both polarities, two cores are required for each phase. It is claimed that the use of a SC winding for saturation reduces the emf induced into the winding when the iron is driven out of saturation.

The IR&D SCFCL is a reactor which normally operates with the magnetic core driven into saturation by a d-c superconducting winding. When a fault current attempts to flow, the magnetic field of the a-c current forces the core out of saturation, the reactor impedance rises, and the current is automatically limited. The automatic self-controlling feature and the relatively compact configuration of the cryogenic container are the major advantages of this device. A disadvantage is the need for two cryo-bushings for the d-c current. Sufficient iron and ampere-turns must be provided to inject sufficient limiting reactance for the highest anticipated faults.

A prototype model is about to be tested. This is a 5 MVA unit. The S/C d-c winding is a "race track" shape, 5 m long and perhaps 2 m wide. It uses NbTi, has about 500 turns, and carries 400 A. Its self field is approximately 3 T. An airgapped magnetic circuit is provided, apparently to control the emf's induced in the d-c coil from the a-c windings.

The normal reactance is about 3%, rising to $\sim 30\%$ to limit fault currents.

First operation models will be 50 MVA, 132 kV. These will use about the same d-c coil size in the 5 MVA unit, but with more iron. This cost is expected to be \$6/KVA or \$600 k for a

3.25 (cont'd)

100 MVA unit; the refrigeration is small and should be independent of MVA; cost will be about \$100 k (5 - 6 l/hr He usage).

The main expected uses will be to delay breaker replacement as load grows and to use as a substation bus tie which will separate the bus when a fault occurs.

VARIABLE SHIELDED IRON INDUCTORS

3.26 Slade A. E., Magnetic Control Device Having Superconductive Gates

A magnetic flux gate is described which varies the mutual inductance between the two coils. Input and output coils are separated by a member formed of SC material. During continuous operation, the SC shield prevents the transfer of power.

Passing current through an auxiliary coil formed around the SC member drives it into the resistive state. Magnetic flux is now able to pass between the input and output coils, delivering power to the secondary circuit.

3.27 Slade A. E., Superconductive Switch Element

A variable inductor is described which consists of an iron core plated with a SC skin. A coil in series with the power circuit is wound around this composite core. During continuous operation, the SC shields the interior of coil, resulting in a low inductance.

Increase of the current in the coil destroys the shielding ability of the SC skin. Magnetic flux can now penetrate into the iron. The resultant inductance limits the current which can pass through the coil.

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3. EVALUATION CRITERIA

Four generic classes of SCFCL have been identified in the literature search (Section 2.3). These basic types of devices must now be judged in order to determine the "best" concept for future detailed analysis and testing. Criteria must, therefore, be established against which a detailed, quantitative evaluation can be made, and some guidelines to follow in making the ranking will also be noted.

Evaluation criteria are primarily based on system requirements. The performance objectives of a SCFCL are characteristics which the system requires, independent of the operating principles or design of the SCFCL itself. The parameters shown in Table 3.1 must be determined from system analysis, and a successful SCFCL must be able to achieve all of these objectives.

In order to determine whether one of the SCFCL concepts can meet these performance objectives, a typical device design must be carried out in sufficient detail to derive numerical values for all required device characteristics. Technical feasibility will be the primary consideration. Analysis of a typical design for one of the basic concepts will lead to one of several possible conclusions:

1. All performance characteristics are met - technical feasibility established.
2. Some performance characteristics are not achieved but judgment indicates feasibility with some design changes.

TABLE 3.1

OPERATING PARAMETERS - SCFCL

(Adapted from Ref. 1.11)

1. Define the system in which the SCFCL will operate; circuit configuration, machine, transformer and line constants; voltage levels; presence of other superconducting devices; contingency scenarios.
2. Currents; rated and maximum allowed continuous current; available short circuit current; maximum allowable ("limited") short circuit current; available and "limited" major loop (peak) asymmetrical currents.
3. Impedance; resistance or inductive reactance required to achieve the required current limits.
4. Voltage; continuous operating voltage, voltage during limiting operation, system BIL requirement.
5. Speed, energy, duty; allowable duration of "limited" current, absorbed energy, required reset speed, total number of operations, coordination with circuit breakers.
6. Stability; constraints on impedance, speed, etc., imposed by stability limits of the system.

3. Some performance characteristics are not achieved and judgment is that technical feasibility cannot be achieved.
4. Further testing of key elements of the concept is required in order to be able to carry out a complete feasibility analysis.

Once technical feasibility of a concept has been established, then a preliminary economic analysis should be made to make sure that there are no major cost factors which would rule out the device from an economic standpoint.

**4. SYSTEM STUDIES TO ESTABLISH REQUIRED
PERFORMANCE PARAMETERS**

4. SYSTEM STUDIES TO ESTABLISH REQUIRED

PERFORMANCE PARAMETERS

Performance parameters of a SCFCL cannot be derived independent of the system in which the current limiter is to operate, and so a typical system (or systems) must be identified in order to specify meaningful requirements. In the literature search, several example systems have been found, including the Long Island Light Co. (1.4), the Northwest (1.3) and the Philadelphia Electric (1.1) studies. The latter (Philadelphia Electric) example system will be adapted for our study since it encompasses projected future power levels with sufficient complexity to give a realistic result and yet not too extensive to require involved, time-consuming and costly computations.

The system, shown under normal operating conditions in Figure 2, consists of a radial and a network version. It employs three parallel superconducting cables to a "mid-site" bus. The network model also has a parallel overhead line.

Figures 2 - 14 illustrate the results of short circuit analyses for faults at each bus, for the following cases:

1. Conventional machines and transformers
2. Superconducting machines and transformers
3. Conventional machines and transformers, one transmission line out of service.
4. Superconducting machines and transformers, one transmission line out of service.

A sample calculation is included as Appendix A to show the computation techniques which were used. The results are summarized in Table I and discussed in the following paragraphs:

1. Generator and transformer fault currents are higher for a fault at the generator bus (bus A), as expected. These are about 3X rated current when conventional machines and transformers are employed but up 4.5X rated using superconducting machines.
2. Superconducting cable symmetrical fault currents could reach 4X their normal operating current.
3. If the system voltage were lower than 230 kV, the available fault current would be higher.
4. Faults within the cable or at other busses would lead to lower currents due to the current-limiting action of added system impedance.
5. The following possible advantages of SCFCL's should be evaluated by continued system studies:
 - a. The lower fault current will allow use of lower rating circuit breakers, transformers and generators.
 - b. The lower fault current will prevent the need for expensive sequential breaker tripping schemes, as employed in Ref. (1.1). These sequential tripping arrangements also increase interrupting time by one-half cycle (1.1).
 - c. Bus runs will not have to be designed to handle the extremely high bus fault currents which have been calculated here.

SHORT CIRCUIT CURRENTS

TABLE 1

- Cases:
1. Using conventional machines
 2. Using superconducting machines
 3. Using conventional machines with one line out of service
 4. Using superconducting machines with one line out of service

FAULTED BUS		A				B			
CASES		1	2	3	4	1	2	3	4
RADIAL SYSTEM	Bus Fault Duty Total Short Circuit Current kA	128	171.2	122.1	165.3	130	153	124.4	142.5
	Generator Fault Current kA	70.4	<u>113.6</u>	70	113.6	55	78.1	49.5	67.6
	Current Through SC Cable kA	19.2	19.2	25.85	25.85	18.4	26	24.75	<u>33.8</u>
NETWORK SYSTEM	Bus Fault Duty Total Short Circuit Current kA	145.7	189.3	138.5	182.1	134.4	150	124	135
	Generator Fault Current kA	70	<u>113.6</u>	70	113.6	45	62.7	38	50.7
	Current Through SC Cable kA	17.1	17.1	22.15	22.45	20	25.3	25.5	<u>30.7</u>

Future directions of the system study will include the following steps:

1. Establish fault current limits for the various system components.
2. Calculate the amount of SCFCL resistance or inductance needed to reduce fault currents to the limits set in step 1.
(Some preliminary calculations on the Long Island Light system are included as Appendix B).
3. Calculate transient stability and required fault clearing times to determine the effect of inserting the SCFCL impedances and to define the reset speed which the device must exhibit. (Some preliminary transient analysis calculations are included as Appendix C.)
4. Finally, determine the voltage across the SCFCL during fault conditions to set the dielectric/withstand requirements of the device.

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FIGURE (1) - NORMAL OPERATION AT RATED POWER

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FIGURE (2) - FAULT AT BUS A

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FIGURE (3) - FAULT AT BUS B

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FIGURE (4) - FAULT AT BUS C

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FIGURE (5) - FAULT AT BUS D

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

SUPERCONDUCTING MACHINES

FIGURE (6) - FAULT AT BUS A

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

SUPERCONDUCTING MACHINE

FIGURE (7) - FAULT AT BUS B

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

SUPERCONDUCTING MACHINE

FIGURE (8) - FAULT AT BUS C

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FAULT CURRENT CALCULATIONS WITH ONE LINE OUT

FIGURE (9) - FAULT AT BUS A

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FAULT CURRENT CALCULATIONS WITH ONE LINE OUT

FIGURE (10) - FAULT AT BUS B

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FAULT CURRENT CALCULATIONS WITH ONE LINE OUT

FIGURE 11 -- FAULT AT BUS C

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

FAULT CURRENT CALCULATIONS WITH ONE LINE OUT

FIGURE (12) - FAULT AT BUS D

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

SUPERCONDUCTING MACHINE WITH ONE LINE OUT

FIGURE 13 - FAULT AT BUS A

RADIAL SYSTEM

NETWORK SYSTEM

NOTE: IMPEDANCES ARE IN PERCENT ON A 100 MVA BASE

SHORT CIRCUIT DIAGRAMS 230 KV SUPERCONDUCTING CABLE 3 LINES IN PARALLEL

SUPERCONDUCTING MACHINE WITH ONE LINE OUT

FIGURE (14) - FAULT AT BUS B

APPENDIX A

APPENDIX A

Given the network of Figure 1-A. The impedances of the system are all reactive, but the common j term has been omitted to simplify the procedure.

Formation Of The Short-Circuit Matrix

The conventional methods will require a complete and separate solution for each and every condition of fault, the short circuit impedance matrix will in itself imply a complete solution regardless of which bus is faulted. This is but one of the several advantages of this method. The general procedure of forming the matrix is as follows:

1. Determine the buses to be retained in the equivalent.
2. Write loop equations in a specified manner. The tree-link criteria can be used to guarantee the sufficient number of independent loops. Loops are not chosen arbitrarily here, but several requirements should be met.
 - a. One and only one loop current passes through each fault bus.
 - b. All other loop currents will flow only within the passive network.
3. Use matrix partitioning to eliminate the internal loop currents which flow within the passive network.

$$[V] = [Z] [I]$$

$$\begin{bmatrix} 1.0 \\ 1.0 \\ 1.0 \\ 1.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{bmatrix} = \begin{bmatrix} .3549 & 0 & 0 & 0 & .3549 & .3549 & 0 \\ 0 & .2335 & 0 & 0 & -.2335 & 0 & 0 \\ 0 & 0 & .5325 & 0 & 0 & -.5325 & .5325 \\ 0 & 0 & 0 & .5288 & 0 & 0 & -.5288 \\ \hline .3549 & -.2335 & 0 & 0 & 1.3884 & .3549 & 0 \\ .3549 & 0 & -.5325 & 0 & .3549 & 1.0374 & -.5325 \\ 0 & 0 & .5325 & -.5288 & 0 & -.5325 & 1.4613 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \end{bmatrix}$$

$$[V] = \begin{bmatrix} z_1 & z_3 \\ \hline z_2 & z_4 \end{bmatrix} [I]$$

$$Z_4 = \begin{bmatrix} 1.3884 & .3549 & 0 \\ .3549 & 1.0374 & -.5325 \\ 0 & -.5325 & 1.4613 \end{bmatrix}$$

$$Z_4^{-1} = \begin{bmatrix} .81 & -.361 & -.124 \\ -.361 & 1.33 & .485 \\ -.124 & .485 & .897 \end{bmatrix}$$

The loop currents I_5, I_6, I_7 are eliminated by matrix partitioning

$$\bar{z}_{sc} = \bar{z}_1 - \bar{z}_2 \bar{z}_4^{-1} \bar{z}_3$$

$$\bar{z}_4^{-1} \bar{z}_3 = \begin{bmatrix} .81 & -.361 & -.124 \\ -.361 & 1.33 & .485 \\ -.124 & .485 & .897 \end{bmatrix} \begin{bmatrix} .3549 & -.2335 & 0 & 0 \\ .3549 & 0 & -.5325 & 0 \\ 0 & 0 & .5325 & -.5288 \end{bmatrix}$$

$$= \begin{bmatrix} .159 & -.189 & .126 & .066 \\ .344 & .085 & -.45 & -.256 \\ .128 & .029 & .22 & -.474 \end{bmatrix}$$

$$\bar{z}_2 \bar{z}_4^{-1} \bar{z}_3 = \begin{bmatrix} .3549 & .3549 & 0 \\ -.2335 & 0 & 0 \\ 0 & -.5325 & .5325 \\ 0 & 0 & -.5288 \end{bmatrix} \begin{bmatrix} .159 & -.189 & .126 & .066 \\ .344 & .085 & -.45 & -.256 \\ .128 & .029 & .22 & -.474 \end{bmatrix}$$

$$Z_2 Z_4^{-1} Z_3 = \begin{bmatrix} .179 & -.037 & -.115 & -.067 \\ -.037 & .044 & -.029 & -.015 \\ -.115 & -.03 & .357 & -.116 \\ -.068 & -.0153 & -.116 & .25 \end{bmatrix}$$

$$Z_{sc} = Z_1 - Z_2 Z_4^{-1} Z_3$$

$$= \begin{bmatrix} .3549 & 0 & 0 & 0 \\ 0 & .2335 & 0 & 0 \\ 0 & 0 & .5325 & 0 \\ 0 & 0 & 0 & .5288 \end{bmatrix} - Z_2 Z_4^{-1} Z_3$$

$$\therefore Z_{sc} = \begin{bmatrix} .1759 & .037 & .115 & .067 \\ .037 & .1895 & .029 & .015 \\ .115 & .03 & .1755 & .116 \\ .068 & .0153 & .116 & .2788 \end{bmatrix} \rightarrow *$$

$\therefore$ The current flowing out of the fault (with bus K faulted) is

$$I_K = \frac{1.0}{Z_{KK}} \text{ p.u. (bus K faulted)}$$

$$I_1 = \frac{1.0}{Z_{11}} = \frac{1.0}{.1759} = 5.685 \text{ p.u.} \\ \approx 142 \text{ kA}$$

$$I_2 = \frac{1.0}{Z_{22}} = \frac{1.0}{.1895} = 5.277 \text{ p.u.} \\ \approx 132 \text{ kA}$$

$$I_3 = \frac{1.0}{Z_{33}} = \frac{1.0}{.1755} = 5.698 \text{ p.u.} \\ \approx 142 \text{ kA}$$

$$I_4 = \frac{1.0}{Z_{44}} = \frac{1.0}{.2782} = 3.5868 \text{ p.u.} \\ \approx 89.7 \text{ kA}$$

To obtain the branch current I_{ij} flowing in the original network of Figure 1-A

$$I_{ij} = \frac{Z_{jk} - Z_{ik}}{Z_{kk} Z_{\text{branch}}} \quad (\text{bus K faulted})$$

Insertion Resistance Calculations:

It is desirable to compute the value of a fixed resistor required to achieve a specified fault current limiting factor.

Incorporating the Thévenin equivalent circuit with the fault current limiter network, and assuming symmetrical faults, a value of insertion resistance, R , can be found for a specified fault current limiting factor, F

$$\text{Fault Current} = \frac{1.0 \text{ p.u.}}{Z \text{ p.u.}} \quad t < 0 \quad (1)$$

Before open the switch

after opening the switch ($t > 0$), the current through the resistance, R , which represents the fault current at steady state is

$$I_{ss} = \frac{1.0}{Z+R} \quad (2)$$

From equations (1) and (2), then

$$I_{ss} = I_{\text{Fault}} \frac{Z}{Z+R} \quad (3)$$

Assuming now that the resistive component of the equivalent circuit impedance is negligible, i.e.:

$$Z = r + jx \quad (4)$$

$$\text{where } r = 0$$

x = equivalent reactance of the system.

then, equation (3) can be rewritten as follows:

$$I_{ss} = I_{\text{Fault}} \left| \frac{jx}{jx+R} \right| \quad (5)$$

thus,

$$\left| \frac{I_{ss}}{I_{Fault}} \right| = \frac{X}{\sqrt{X^2 + R^2}} \quad (6)$$

This ratio of steady state current to fault current is defined as the fault current limiter F.

then

$$F = \frac{X}{\sqrt{X^2 + R^2}} \quad (7)$$

Thus for a given power system with known voltage and power rating, the Thevenin impedance can be found. Then, by specifying the desired fault current limiting factor, F, the necessary value of insertion resistance can be found for either source protection or SC cable by solving equation (7) for R with appropriate equivalent impedance.

$$R = \sqrt{X^2 \left(\frac{1}{F^2} - 1 \right)} \quad (8)$$

Equation (8) provides a direct means by which the insertion resistance, R, can be calculated.

Referring to short circuit studies which were investigated in the previous preliminary investigation pertaining to superconducting cable. Determining the value of inserting resistor, R, will be based on the same system used before in short circuit studies.

As far as superconducting cable is concern, William Keller has stated that the fault current should be limited to about 500 rms/cm of conductor circumference. Therefore, steady state fault current should be limited to this value.

$$I_{ss/cable} = 500 \times 2\pi \times 3.01 \approx 9.5kA \quad (9)$$

Note that

$$I_{\text{rated continuous current}} = 8kA \quad (10)$$

$$\text{Base Impedance} = \frac{(345)^2}{4800} = 24.8\Omega$$

Determining Insertion Resistance Value With Conventional Machines:

From short circuit studies, it shows that fault at Bus A is more severe than Bus B as far as superconducting cable is concern, then a fault current limiter is required at Bus B primarily to protect superconducting cable and another fault current limiter is required at Bus A primarily to protect the machine and SC cable as well.

Required Resistance At Bus B:

$$F_{\text{Cable}} = \frac{I_{ss}}{I_{\text{Fault}}} = \frac{9.5}{16.5} \approx .58 \quad (11)$$

Substituting equation (11) into equation (8), then

$$R_1 = \sqrt{(.248)^2 \left[\frac{1}{(.58)^2} - 1 \right]} = 0.35 \text{ p.u.} \quad (12)$$

Required Resistance At Bus A:

Resistance R_2 is required at Bus A in order to protect machine first and cable second.

Assuming that I_{ss} is the same, the

$$F_{\text{Machine}} = \frac{I_{ss}}{I_{\text{Fault Machine}}} = \frac{9.5}{18.25}$$

$$= .52$$

(13)

Similarly,

$$R_2 = \sqrt{(.44)^2 \left[\frac{1}{(.52)^2} - 1 \right]}$$

$$= .72 \text{ p.u.}$$

(14)

Table (1) summarizes the required resistance at Bus A and Bus B for both conventional machine and superconducting machine.

TABLE 1
Required Insertion Resistance

	BUS A					BUS B				
	I_{Fault} Generator Current	I_{ss} kA	F	R_2 p.u.	R_1 Ω	I_{Fault} per cable	I_{ss} kA	F	R_1 p.u.	R_1 Ω
Conventional Machine	18.25	9.5	.52	.72	17.8	16.2	9.5	.58	0.35	8.7
Superconducting Machine	25	9.5	.38	.61	15.0	17.2	9.5	.55	0.35	9.5

APPENDIX C

APPENDIX C

Short Circuit Calculations:

A. Conventional Generator and Transformer

1. Short Circuit At Bus A

$$\text{Equivalent Impedance } Z_{th} = \frac{.44 \times .168}{.44 + .168} = .122 \text{ p.u.}$$

$$\text{Short Circuit Current } I_{sh} = \frac{4800 \times 10^6}{\sqrt{3} \times 345 \times 10^3 \times .122} = 65.8 \text{ kA}$$

The Generators contribute a current of

$$65.8 \times 10^3 \times \frac{.168}{.44 + .168} \approx 18.2 \text{ kA}$$

Each superconducting cable will carry current of

$$65.8 \times 10^3 \times \frac{.44}{.44 + .168} \times \frac{1}{2} = 23.8 \text{ kA}$$

Then peak current in the first cycle fully offset

$$\begin{aligned} \sqrt{2} \times 23.8 \times 2 &= 67.3 \text{ kA} \\ &\approx 8.5 \text{ times rated current per cable} \end{aligned}$$

2. Required Resistance At Bus B

$$F = \frac{I_{ss}}{I_{Fault}} = \frac{9.5 \times 10^3}{23.8 \times 10^3} = .4$$

Where

$$\begin{aligned} I_{ss} &\equiv \text{steady state fault current} \\ &= 9.5 \text{ kA as previously calculated} \end{aligned}$$

$$I_{rated} = 8 \text{ kA continuous current}$$

Then

$$\begin{aligned} \text{Required resistance } R &= \sqrt{X^2 \left(\frac{1}{F^2} - 1 \right)} \\ &= \sqrt{(.168)^2 \left[\frac{1}{(.4)^2} - 1 \right]} \\ &= .385 \text{ p.u.} \\ &= 9.5 \text{ ohms} \end{aligned}$$

3. Short Circuit At Bus B

Similarly

$$Z_{th} = \frac{.1 \times .508}{.1 + .508} = .084 \text{ p.u.}$$

$$I_{sh} = \frac{4800 \times 10^6}{\sqrt{3} \times 345 \times 10^3 \times .084} = 95.6 \text{ kA}$$

The Generators contribute a current of

$$95.6 \times \frac{.1}{.1 + .508} = 15.8 \text{ kA}$$

Each superconducting cable will carry current of

$$\frac{15.8}{2} = 7.9 \text{ kA}$$

4. Required Resistance At Bus A

It is clear that short circuit at Bus B is not serious as far as the superconducting cable is concerned. Thus resistance r is required at Bus A in order to protect machine first and cable second.

Assuming I_{ss} is the same, and using the higher machine fault current

$$F_{\text{machine}} = \frac{I_{ss}}{I_{\text{Fault Machine}}} = \frac{9.5}{18.2} = .52$$

Similarly

$$r = \sqrt{(.44)^2 \left[\frac{1}{(.52)^2} - 1 \right]} = .72 \text{ p.u.} \\ = 17.8 \text{ ohms}$$

According to the previous calculations, Figure (2) shows the locations of FCL as far as superconducting cable is concerned. It should be noted that location of FCL at Bus B protects only the superconducting cable but not the infinite bus. As we have seen short circuit at Bus B will draw a severe fault current from the infinite bus, this is outside the scope of this project

B. Superconducting Generator And Transformer

Similar calculations were carried out, see Table 1 for comparison

Conventional

Superconducting

I_{sh} kA	Generator Current kA	Fault Current Per Cable	r p.u.	I_{sh} kA	Generator Current kA	Fault Current Per Cable	R p.u.
65.8	18.2	23.8	.72	95.6	15.8	7.9	.39
73	25	24	.72	100.5	20.6	10.3	.39

TABLE 1

Transient System Stability:

The purpose of this study is to investigate the effect of FCL inserted resistance, during and after fault had been cleared, on the system stability.

Considering 3 phase fault at Bus A, as discussed before, during fault there is no power delivered to the infinite bus, therefore the inserted resistance has no direct effect. However, after fault had been cleared, drop one of the line, (about 3 cycles from time the fault started) assume that FCL resistance is still connected, then

Before Fault

The impedance between the conventional generator and the infinite bus is

$$X = .1 + .068 + .18 + .32 = 0.668 \text{ p.u.}$$

During Fault

The impedance between the generators and the infinite bus is considered infinite.

After Fault

After the fault is cleared by opening the circuit breaker at both ends of the faulted line near Bus A, assuming that FCL inserted resistance is still connected, then, the impedance between the conventional generator and the infinite bus is

$$\begin{aligned} Z &= .72 + .78 + j (.1 + .136 + .18 + .32) \\ &= 1.5 + j .736 \\ &= 1.67 \angle 26^\circ \end{aligned}$$

Assume that Bypass switch will short the resistance after the fault had been cleared by approximately one cycle, then

$$Z = j .736$$

The Power Angle Of Synchronous Machine:

Assume that the voltages at generator bus and infinite bus are

$$E_g = |E| \angle \delta \quad \text{and} \quad V_t = |V| \angle 0^\circ$$

Where:

V and E are expressed in per unit

δ is called the torque angle or power angle of the machine

Then

$$I = \frac{|E| \angle \delta - |V|}{R + jX}$$

And

$$I^* = \frac{|E| \angle -\delta - |V|}{R - jX}$$

Therefore

$$\begin{aligned} P + jQ &= VI^* \\ &= \frac{|V| |E| \angle -\delta - |V|^2}{R - jX} \\ &= \frac{VE \angle -\delta - V^2}{R - jX} \cdot \frac{R + jX}{R + jX} \end{aligned}$$

Then the real part of the last equation

$$P = \frac{VER \cos(-\delta) - V^2 R + VEX \sin(-\delta)}{R^2 + X^2}$$

Put

$$Z^2 = R^2 + X^2$$

$$\theta = \tan^{-1} \frac{X}{R}$$

Then

$$P = \frac{VEZ \cos(\theta - \delta) - ZV^2 \cos \theta}{Z^2}$$

$$P = \frac{VE \cos(\theta - \delta)}{Z} - \frac{V^2 \cos \theta}{Z}$$

Special Case:

$$\text{When } R = 0$$

$$\text{Then } P = \frac{VE \sin \delta}{X}$$

Equations For The Power Output Of The Generator Are:

Assume $V = 1.0$, $E = 1.05$ p.u.

Before The Fault:

$$P_{\max} \sin \delta = \frac{1.0 \times 1.05}{.668} \sin \delta = 1.57 \sin \delta$$

During The Fault:

$$P''_{\max} \sin \delta = 0$$

After The Fault:

A. With FCL inserted resistance

$$\begin{aligned} P' &= \frac{1.0 \times 1.05 \cos(26-\delta)}{1.67} - \frac{1.0}{1.67} \cos 26 \\ &= .63 \cos(26-\delta) - .54 \end{aligned}$$

Where,

$$\begin{aligned} Z &= \sqrt{(1.5)^2 + (.736)^2} \\ &= 1.67 \\ \theta &= \tan^{-1} \frac{.736}{1.5} \\ &= 26^\circ \end{aligned}$$

B. Without FCL inserted resistance

$$\begin{aligned} P' \sin \delta &= \frac{VE}{X} \sin \delta \\ &= \frac{1.0 \times 1.05}{.736} \sin \delta \\ &= 1.42 \sin \delta \end{aligned}$$

In order to determine the initial angle δ_0 , assuming we have 1.0 p.u. power, then

$$1.0 = 1.57 \sin \delta_0$$

$$\delta_0 = 39.56^\circ \approx 40^\circ$$

See Figure (3)

The Swing Curve

The calculation of swing curve was carried out assuming that the clearing time was 4.5 cycles. The FCL resistance was connected to the system for about one cycle after fault had been cleared. See Table (2).

Computations of swing curve for fault cleared at $t = .075$ seconds, i.e., 4-5 cycles and inserted resistance is shorted within one cycle after fault had been cleared.

$\Delta t = .01$ second Time Interval

$M = 2.78 \times 10^{-4} \text{ s}^2/\text{Electrical degrees (Based on H, Generator Inertia = 3)}$

t sec.	Pe	Pa	$\frac{\Delta t^2}{M} \text{ Pa}$	$\Delta \delta_n$	δ_n
0-	1.0	0.0			40.0
0+	.0	1.0			40.0
0Avg.		0.5	.18	.18	40.0
0.01	0.0	1.0	.36	.54	40.18
.02	0.0	1.0	.36	.9	40.54
.03	0.0	1.0	.36	1.26	41.44
.04	0.0	1.0	.36	1.62	42.7
.05	0.0	1.0	.36	1.98	44.32
.06	0.0	1.0	.36	2.34	46.3
.07	0.0	1.0	.36	2.7	48.64
.08	.041	0.959	.345	3.045	51.34
.09	.014	0.986	.355	3.4	54.385
.10	1.20	.20	0.072	3.328	57.785
.11	1.243	.243	0.087	3.241	61.113
.12	1.28	.28	.1	3.141	64.354
.13	1.31	.31	.11	3.031	67.5
.14	1.34	.34	.122	2.9	70.531
.15	1.36	.36	.13	2.77	73.43
.16	1.38	.38	.14	2.63	76.2
.17	1.393	.393	.141	2.49	78.83
.18	1.4	.4	.144	2.26	81.32
.19	1.411	.411	.148	2.112	83.58
.20	1.416	.416	.149	1.963	85.69
.21	1.42	.42	.151	1.812	87.65
.22	1.42	.42	.151	1.661	89.46
.23	1.42	.42	.151	1.51	91.12
.24	1.42	.42	.151	1.359	92.62
.25	1.416	.416	.150	1.21	93.98
.26	1.414	.414	.149	1.061	95.19
.27	1.411	.411	.148	.913	96.25
.28	1.4	.4	.144	.769	97.16
.29	1.4	.4	.144	.625	97.929
.29	1.4	.4	.144	.481	98.55
.30	1.4		.144		99.03

Summary Conclusions:

1. Reduce the equivalent impedance of the infinite bus causes fault current peak in the superconducting cable could reach 9 times the rated current.
2. It is recommended to locate the FCL in the following positions:
 - a. At Bus B, possible location is at the cable terminal since we are looking for cable protection, however, this location will not provide any protection to the infinite bus.
 - b. At Bus A, possible location after transformer and before the Bus. This location will provide protection to both cable and generator.
3. From the stability study. The system is stable if the fault is cleared after 4-5 cycles (should be 3 cycles only) and allow one more cycle to remove the FCL inserted resistance from the network.
4. Comments:

The long subtransient time constant for superconducting machine, tends to make the transient stability dependent on the subtransient reactance rather than the transient reactance as with a conventional machine.

	Conventional	SC
Subtransient Time Constant	.04	.26 seconds
Transient Time Constant	0.8	23.0 seconds

The reduced synchronous and subtransient reactance tend to compensate for the lower inertia of the rotor, yielding a critical fault clearing time equal to somewhat better than conventional machines.

A. Conventional Generator And Transformer

B. Superconducting Generator And Transformer

FIGURE (1) - Reactance Diagram

FIGURE (2) - FCL Locations

Equal Area Criterion Applied To Fault Clearing When Power Is Transmitted During The Fault. Areas A_1 and A_2 are Equal

FIGURE (3) - Power Angle Curve