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SUPERCONDUCTING FAULT CURRENT LIMITER AND INDUCTOR DESIGN*

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Abstract

A superconducting fault current limiter (SFCL) that uses a biased superconducting inductor in a diode or thyristor bridge circuit was analyzed for transmission systems in 69, 138, and 230 rms kV utility transmission systems. The limiter was evaluated for costs with all components—superconducting coil, diode and/or SCR power electronics, high voltage insulation, high voltage bushings and vapor cooled leads, dewar, and refrigerator—included. A design was undertaken for the superconducting cable and coils for both diode and SCR 69 kV limiter circuits.

Scoping Study

The superconducting fault current limiter under study is based upon a circuit proposed by Westinghouse Electric Corporation and modified in an alternate circuit by replacing the diodes with thyristors.[1] See Fig. 1. Components in the diagram D1, D2, D3, and D4 are the diode or SCR bridge; A1, A2, and A3 are surge arresters; L is the superconducting reactor; V_b represents the bias power supply; and CB is the two cycle circuit breaker or low current disconnect switch. X represents the generator side impedance, V is the voltage generator source, i_L is the reactor current, i_{ac} is the load current, and the broken arrow indicates a load side fault.

The coil functions as a d.c. reactor with a small a.c. ripple superimposed, except during faults, when a current surge must be suppressed. Limiters for operation on electric utility power systems nominally rated 69, 138, or 230 kV at 1.2 kA rms have been considered. The corresponding steady state reactor current considered becomes 2.0 kA for the SFCL coil. The optimum transient surge current can then be shown to be 4 kA.

The diode circuit of Westinghouse requires no external switching controls to limit the fault current surge; however, this current limiter must be augmented with an inline circuit breaker. Such breakers are known to be single or two cycle breakers. Single cycle breakers, which can be triggered to interrupt the current on the first cycle of the fault current surge, are not sufficiently reliable for current limiter application and the design must be for a two cycle current interrupter.

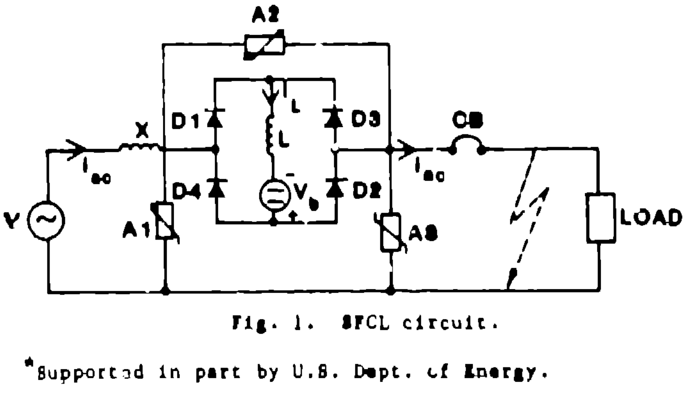

Fig. 1. SFCL circuit.

An improvement on the diode circuit substitutes SCRs for the diodes and requires switching capability. The advantage of the SCR circuit is that the fault current can be suppressed in one-half cycle and will be zero in one and a half cycles. Under these conditions, a high current interrupter or circuit breaker is not needed; and a low current disconnect switch can be used to clear the faulted power line. For the conditions presented, the scoping parameters of Table I were established.

Studies were performed to examine optimum superconducting coil size and energy storage. Relative costs were developed to determine sensitivity to field from 1 to 10 T. Costs are lower at low fields, ~ 1 to 3 T, by a factor of about 2, compared with costs at high fields, ~ 8 to 10 T. Costs vary only about 20 to 30% as a function of coil length from ~ 60 to 250 cm in the low field region and with corresponding coil thickness from ~ 8 to 2 cm. The lower costs are for the shorter lengths. For these reasons and the low cost sensitivity to field at 1 to 3 T, a solenoidal length to mean diameter of unity and a maximum field of 2.5 T during fault were chosen for more refined study.

Optimization for minimum stored energy and for minimum inductance, in this case with a fixed maximum current of 4 kA, to meet reasonable utility power line requirements resulted in peak energy storage values of 4.8 and 9.6 MJ for the 1 and 2 cycle diode circuit and 2.4 MJ for the half cycle SCR circuit. Thus, the superconducting reactor is appreciably smaller for the half cycle SCR circuit.

The results of the refined study are given in Table II for the scoping parameters of Table I and unity length to mean diameter ratio. Fixing the field at 2.5 T causes the inductance and energy stored to deviate some from the optimum. The inductance was determined from

$$L = \frac{2}{\pi}\sqrt{\frac{2}{3}}\,\frac{V_{rms}\,t}{I_{dc}} .$$

The thickness is nearly constant to the precision of the calculation and is based upon cryostability considerations. These considerations are that two-thirds of the conductor surface is available for heat transfer and that the heat transfer coefficient from the conductor surface to the liquid helium is 0.25 W/cm^2.

TABLE I

SFCL SCOPING PARAMETERS

Voltage, kV, rms	69,138,230
AC current, kA, rms	1.2
DC reactor current, kA	2.0
Reactor maximum surge current, kA	4.0
Circuits considered	
Diode, cycles	2
SCR, cycles	0.5

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TABLE II

REFINED SFCL COIL PARAMETERS

Voltage kV, rms	Cycles	Circuit	Inductance mH	Length cm	Thickness cm	Turns	B_{max} T	Energy MJ
69	2	diode	330	55	5.2	680	2.5	2.6
138	2	diode	660	70	5.2	845	2.5	5.3
230	2	diode	1100	83	5.2	1000	2.5	8.8
69	0.5	SCR	85	35	5.2	430	2.5	0.7
138	0.5	SCR	165	44	5.2	545	2.5	1.3
230	0.5	SCR	275	52	5.2	640	2.5	2.2

Cost Study

A superconductor cost of $2.75/kA-m at 2.5 T is used. The power electronics costs are for somewhat improved commercial components. High voltage insulation costs for accepted BIL ratings are devised from a coordinated insulation conceptual design for a helical wound layer coil. High voltage bushing costs for introducing current into the dewar are from the superconducting transmission line program. The vapor cooled leads, which are housed within the bushings, are costed from both Brookhaven National Laboratory and Los Alamos experience. Dewar costs are established from knowledge of many commercially available metal dewars and the known costs of a few specialty plastic dewars. The refrigerator cost is a supplier's quotation of $175,000 and is the same for all cases. Tabulated component costs are in Tables III through VII, and the overall SFCL costs are given in Table VIII for a full three phase limiter.

Losses given in Table III are high by a factor of about two because they were calculated for the entire coils going from 1.25 to 2.5 T in 8 ms and returning to 1.25 T in 8 ms with no field gradients considered. The corresponding current change is from 2 to 4 to 2 kA. Coupling losses dominate.

The protection factors of Table IV are the ratios of the series connected diodes or SCRs blocking voltages to the break-away voltages of the surge arresters.

Cost and Loss Comparison

A study performed for the Electric Power Research Institute (EPRI) by Westinghouse Electric Corporation[2] examined resonant circuit fault current limiters with normal conducting reactors. Figure 8-3 of the EPRI report gives costs in 1978 dollars for a 145 kV, 300 MVA current limiter which can be compared with the 138 kV, 287 MVA SFCL of this study. The preferred low loss circuits of the EPRI study at 15 kA peak let through current followed by steady fault current of 2.8 kA cost from $850 to 920 thousand. These same circuits cost from $760 to 1160 thousand for steady fault currents ranging from 2 to 4.4 kA after the peak let through current occurs. These 1978 costs should be inflated by 33 to 40% for comparison with the 1982 amounts listed in Table VIII for the 138 kV circuits. On this basis the SFCL SCR circuits cost close to the same (33% factor) or show some real advantage (40% factor).

Full load losses for the EPRI resonant cirucit limiter rated at 145 kV and 300 MVA are given as a function of steady fault current at about 0.07 to 0.14% of the throughput rating. Full load losses, based on Table IV, are 0.16 and 0.29%, respectively, for the diode and SCR SFCL 138 kV, 287 MVA circuits.

The power electronics of the SCR circuits for the SFCL cost 60 to 80% more than for the diode circuits. Because the SCR circuits permit suppression of the fault current in one-half cycle instead of two, the superconducting coils are smaller and the circuit breakers are replaced by much less costly disconnect switches. The result, see Table VIII, is that the SCR circuits have cost advantages of 79, 77, and 75%, respectively, at 69, 138, and 230 kV.

Superconducting Coil Design

The superconducting coil design was developed for the 69 kV current limiter for both the 1/2 and 2 cycle fault duration, SCR and diode circuits, respectively. The coil design is dominated by the high voltage insulation requirements.

The standard dielectric tests for a 69 kV current limiting reactor, superconducting coil in this case, call for a low frequency test at 160 kV and a Basic Impulse Insulation Level (BIL) test of 350 kV full wave, including a 400 kV chopped wave test. The preliminary designs were based only on the 350 kV BIL. The assumption was made that supercritical helium at 4.5 K and 3.0 atm will be used to cool the superconducting coil.

Type 300 A Mylar, 0.003 in., was selected for the layer insulation. A minimum of thirty nine layers of Mylar will be wrapped around each of the eight layers of the coil. The conductor turn to turn insulation will be provided by the tracking distance between turns along the winding. Dimensions of the design were determined to assure voltage stresses equal to or less than those given in Table IX. The coil design is shown in Fig. 2. Table X gives the coil characteristics for both the 1/2 and 2 cycle fault duration circuits. Not shown in Fig. 2 is the attachment of the 0.030 in. thick inner and outer electrostatic shields to the innermost and outermost coil layer windings at the points where the superconducting cables will go from the coil to the vapor cooled leads. These connections assure uniform voltage grading through the coil. The electrostatic shields do not close electrically upon themselves as cylinders but must have an insulated lap joint. Voltage breakdown between turns is easily prevented by a creepage path greater than 0.040 in. Only the innermost of the eight conductor winding, spacer, and insulation layers is shown in detail in Fig. 2. The stresses listed in the table for the stainless steel strap, co-wound with the cable, include the 100 lb preload, the differential thermal contraction load for cooling to 4.5 K, and the magnetic Lorentz force hoop load.

Superconducting Cable Design

Table XI gives the cable characteristics. Dimensions of the cable are on the high side because compaction occurs during the rectangular forming through a set of Turks head rollers. The extent of compaction is determined only when cable is actually made. Figure 3 shows the cable composed of sixteen subcables wrapped around a Mylar strip in a Rutherford rectangular twisted lay. The Mylar strip prevents shorting among subcables on opposite sides of the cable and, thus, reduces eddy currents. Each subcable is composed of six copper wires wrapped around a superconducting strand all soldered together with Stabrite to reduce eddy currents in the subcable.

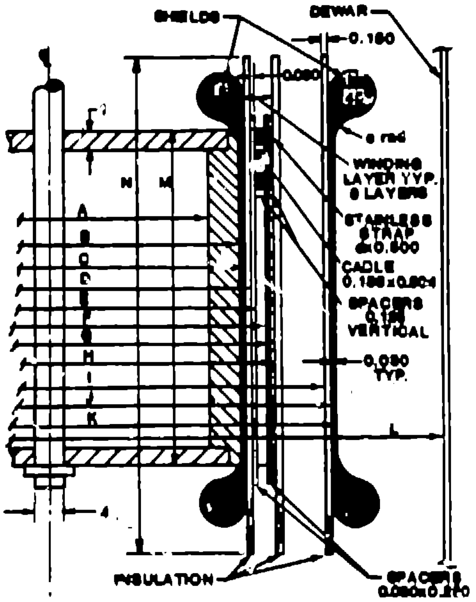

Fig. 2. Superconducting coil, dimensions in inches.

References

1. H. J. Boenig, D. A. Paice, "Fault Current Limiter Using a Superconducting Coil," 1982 App. Superconducting Conf., Knoxville, TN; November 30–December 3, 1982.

2. D. A. Paice, R. P. Putkovich, J. Zubek, J. Bonk, L. Grove, "Controlled Impedance Short Circuit Limiter," Electric Power Research Institute report EPRI EL-857, August 1978.

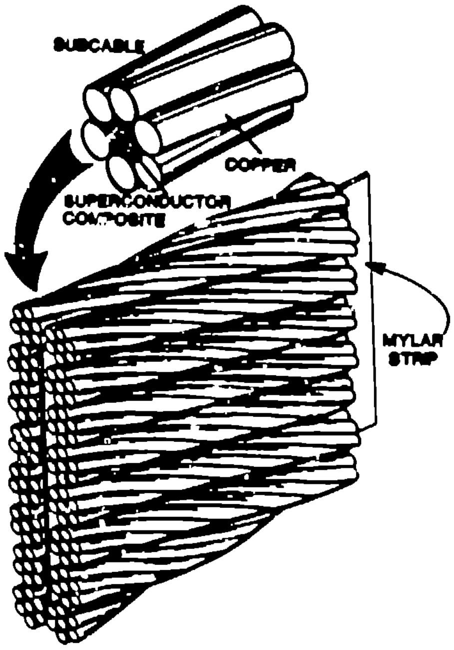

Fig. 3. Superconducting cable.

TABLE III

SFCL COSTS FOR ONE COIL AND CABLE

Voltage kV, rms	Circuit	Cable Length m	Coil Loss kJ	Cable $(10)^3$	Insulation $(10)^3$	Coil[a] $(10)^3$
69	diode	2350	12.4	23.5	6.8	147.8
138	diode	3716	19.6	37.2	16.5	213.6
230	diode	5215	27.5	52.2	31.6	344.8
69	SCR	946	5.0	9.5	2.8	59.8
138	SCR	1507	7.9	15.1	6.5	93.3
230	SCR	2091	11.0	20.9	12.4	129.4

[a] Includes superconducting cable and insulation.

TABLE IV

POWER ELECTRONICS PARAMETERS FOR SINGLE PHASE SFCL

Voltage kV, rms	Circuit	Arrester Break-Away Voltage, kV	Number Diodes/SCRs	Protection Factor	Losses[a] kW
69	diode	75	64	1.54	83
138	diode	150	123	1.54	156
230	diode	190	208	1.50	247
69	SCR	75	80	1.57	143
138	SCR	150	160	1.57	276
230	SCR	190	256	1.51	435

TABLE V

POWER ELECTRONICS COSTS FOR SINGLE PHASE SFCL

Voltage kv, rms	Circuit	Bridge $(10)^3	Bias Supply $(10)^3	Arrester $(10)^3	Breaker $(10)^3	Total $(10)^3
69	diode	60	25	5	30	120
138	diode	100	30	8	60	198
230	diode	180	35	12	100	327
69	SCR	100	25	5	10	140
138	SCR	160	30	8	20	218
230	SCR	290	35	12	33	370

TABLE VI

INSULATION AND ELECTROSTATIC SHIELDING FOR ONE SUPERCONDUCTING COIL

Voltage kV, rms	Circuit	BIL kV	Insulation Cost, $(10)^3 Material	Labor	Shields	Total
69	diode	350	0.6	4.2	2.0	6.8
138	diode	550	1.6	10.1	4.8	16.5
230	diode	750	3.0	19.4	9.2	31.6
69	SCR	350	0.3	1.7	0.8	2.8
138	SCR	550	0.6	4.0	1.9	6.5
230	SCR	750	1.2	7.6	3.6	12.4

TABLE VII

DEWAR, BUSHINGS, AND VAPOR COOLED LEADS FOR ONE COIL

Voltage kV, rms	Circuit	Dewar, $(10)^3 Metal	Plastic	Bushings $(10)^3	Leads $(10)^3
69	diode	10.0	27.0	2.0	40.0
138	diode	16.0	43.0	4.0	40.0
230	diode	22.5	62.0	6.0	40.0
69	SCR	5.0	12.0	2.0	40.0
138	SCR	6.5	18.0	4.0	40.0
230	SCR	9.0	24.0	6.0	40.0

TABLE VIII

SFCL OVERALL COSTS FOR THREE PHASES

Voltage kV, rms	Circuit	Total Cost, $(10)^3 A	B
69	diode	1134	1185
138	diode	1590	1670
230	diode	2396	2514
69	SCR	915	936
138	SCR	1260	1295
230	SCR	1838	1883

A = total cost with metal dewar
B = total cost with plastic dewar

TABLE IX

INSULATION AND HELIUM VOLTAGE STRESSES AT 350 kV BIL

	kV/mm
Across Mylar	30
Creepage	1
Bulk helium	10

TABLE X

COIL CHARACTERISTICS

	Dimension	1/2 Cycle	Both	2 Cycle
Voltage, kV, rms			69	
DC current, kA			2.0	
Maximum surge current, kA			4.0	
Turns		432		680
Layers			8	
Turns/layer		54		85
Interlayer insulation				
Material			type 300 Mylar	
Thickness/layer, in.			0.003	
Number layers			39	
Thickness/layer, in.			0.020	
Number layers			1	
Material			fiberglass-Mylar tape	
Thickness/layer, in.			0.010	
Number layers			1	
Length, in.	N	42.13		61.72
Eighth layer outside diam., in.	J	33.31		49.38
First layer outside diam., in.	D	25.61		41.36
G-10 CR epoxy fiberglass mandrel				
Inside diam., in.	A	22.25		38.00
Outside diam., in.	B	25.25		41.00
Length, in.	M	34.13		53.72
Shields				
Material			aluminum	
Inner, ouside diam., in.	C	25.31		41.06
Outer, outside diam., in.	K	33.37		49.44
Spacers				
Material			G-10CR	
Layer to layer, in.			0.080 W × 0.25	
Length, vertical, in.		34.13		53.72
First set, outside diam., in.	E	25.77		41.52
Second set, outside diam., in.	G	26.20		41.95
Turn to turn, in.			0.125 H × 0.136 W	
Length			variable along turns	
Conductor, first layer, outside diam., in.	F	26.04		41.79
Strap				
Material			304 stainless steel	
Dimensions, in.	d	0.035 × 0.500		0.055 × 0.500
Stress, ksi		2.6		24.3
First layer, outside diam., in.	H	26.27		42.06
Eighth layer, outside diam., in.	I	33.01		49.08
Dewar				
Material			stainless steel	
Inner wall, inside diam., in.	L	45.25		62.50
a, in.		2.75		4.38
b, in.		3.19		4.56
c, radius, in.		2.00		2.00

TABLE XI

SUPERCONDUCTING WIRE AND CABLE CHARACTERISTICS

Wire	
Diameter, in.	0.021
Superconductor	NbTi
Number filaments	1250
Filament diameter, μm	10
Copper to NbTi ratio	1.3
Twist pitch length, in.	0.126
Critical current at 4.5 K and 2.5 T,A	250
Critical current density at 4.5 K and 2.5 T, A/cm^2	2.5 (10)^5
Cable	
First level, subcable, 6 Cu around 1 superconducting strand, Stabrite soldered, twist pitch ~ 0.75 in., R.H.	
Second level, 16 first level in Rutherford lay around Mylar strip, twist pitch ~ 3.0 in., L.H.	
Cable dimensions, in.	0.136 × 0.504
Mylar strip dimensions, in.	0.010 × 0.380
Copper to NbTi ratio in entire cable	15.1