Hybrid superconducting a.c. current limiter extrapolation 63 kV-1 250 A

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Classification
Physics Abstracts
85.25J

Hybrid superconducting a.c. current limiter extrapolation 63 kV-1 250 A

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(*Received 15 July 1993, revised 22 September 1993, accepted 2 November 1993*)

Résumé. — Les courants de court-circuit sur les grands réseaux électriques ne cessent d'augmenter. Dans ce contexte sont apparus les limiteurs supraconducteurs de courant suite au développement des brins supraconducteurs alternatifs. Ces limiteurs peuvent limiter les courants de défaut presque instantanément, sans détection de défaut ni donneur d'ordre et ils sont extrapolables aux hautes tensions. Ils sont fondés sur la transition naturelle de l'état supraconducteur à l'état normal très résistif par dépassement du courant critique d'un enroulement supraconducteur qui limite ou déclenche la limitation. Notre limiteur est composé de deux enroulements en cuivre couplés par un circuit magnétique saturable et d'une bobine supraconductrice à courant réduit par rapport au courant de la ligne. Cette conception permet un câble supraconducteur simple et des pertes cryogéniques réduites mais les contraintes diélectriques en régime de défaut sont importantes. Une maquette (150 V/50 A) a permis de valider expérimentalement cette conception. Nous aborderons l'extrapolation d'un limiteur de taille industrielle (63 kV/1 250 A). Les résultats seront comparés à des limiteurs supraconducteurs résistifs et de type DASC.

Abstract. — Following the developement of a.c. superconducting wires a.c. current superconducting limiters have emerged. These limiters limit the fault currents nearly instantaneously, without detection nor order giver and may be suitable for high voltages. They are based on the natural transition from the superconducting state to the normal resistive state by overstepping the critical current of a superconducting coil which limits or triggers the limitation. Our limiter device consists essentially of two copper windings coupled through a saturable magnetic circuit and of a non inductively wound superconducting coil with a reduced current compared to the line current. This design allows a simple superconducting cable and reduced cryogenic losses but the dielectric stresses are high during faults. A small model (150 V/50 A) has experimentally validated our design. An industrial scale current limiter is designed and the comparisons between this design and other superconducting current limiters are given.

Introduction.

The short circuit power always grows up in the electrical networks as the need for electrical energy increases and the fault levels reach the capabilities of existing equipments. The

nowadays cutting techniques for high voltages are the circuit breakers which open at the zero crossing of the current. The most performing devices open in one cycle, the minimal theoretical delay [1]. Even with these « perfect » circuit breakers, all the components above the fault have to withstand the destructive effects of the short circuit currents during one cycle. That is the reason why the current limiters are very attractive, they guarantee the absence of current excursion above a threshold value reducing considerably the mechanical and electrodynamic stresses for the network.

The limiters could improve also the control of the network as they could decrease the voltage drops of the transformers. For instance the short circuit currents are largely defined by the short circuit impedances of the transformers which are then relatively high (15 %) to limit the fault currents. These high short circuit impedances introduce, in normal operation, voltage drops and reactive power consumptions. As the limiters fix themselves the fault currents, they make it possible to reduce the short circuit transformer impedances.

The limiters should increase the power transmission capability and improve the dynamic stability due to the reduction of the fault current duration [1].

Unfortunately the classical current limiters like fuses or devices using power electronic components have limitations in voltage and there is no current limiter nowadays for the high voltage networks.

1. Superconducting current limiter : general characteristics.

The idea to use the quench of a superconducting coil above its critical current to limit an a.c. current dates from the seventies [2] but only the developement of the a.c. superconducting wires in the eighties [3] has made experimental realisations possible.

Superconducting current limiters naturally integrate detection and operation and are suitable for high voltages : they are a promising development axis for high voltage networks.

The superconducting material used for nowadays devices is NbTi, with a working temperature lower than 5-6 K. The cost of the losses at low temperatures is high due to the low efficiency of helium refrigerators and the cryogenic losses have to be reduced as far as possible. The cryogenic tanks have very low losses. The coils wound with high performance a.c. multifilamentary superconducting wires have reduced losses under low a.c. fields [4]. The current leads which connect the superconducting coil to the external power supply have losses proportional to the current and they are an important part of the total cryogenic losses. Thus it is interesting to operate at low current. The use of hybrid current leads with high T_c materials and copper would decrease these losses.

2. Resistive limiter.

It consists of a superconducting coil with a low inductance put in series with the system to protect. This device has been successfully tested up to significant power levels [5, 6]. Simple in its principle and realization it has nevertheless a drawback : the superconducting coil has to carry the full current of the line. In the present state of the art some difficulties appear for high a.c. current superconducting cables. Moreover the losses in the current leads are too high for low voltage applications. These problems make to consider other configurations even if the resistive limiter remains an attractive solution.

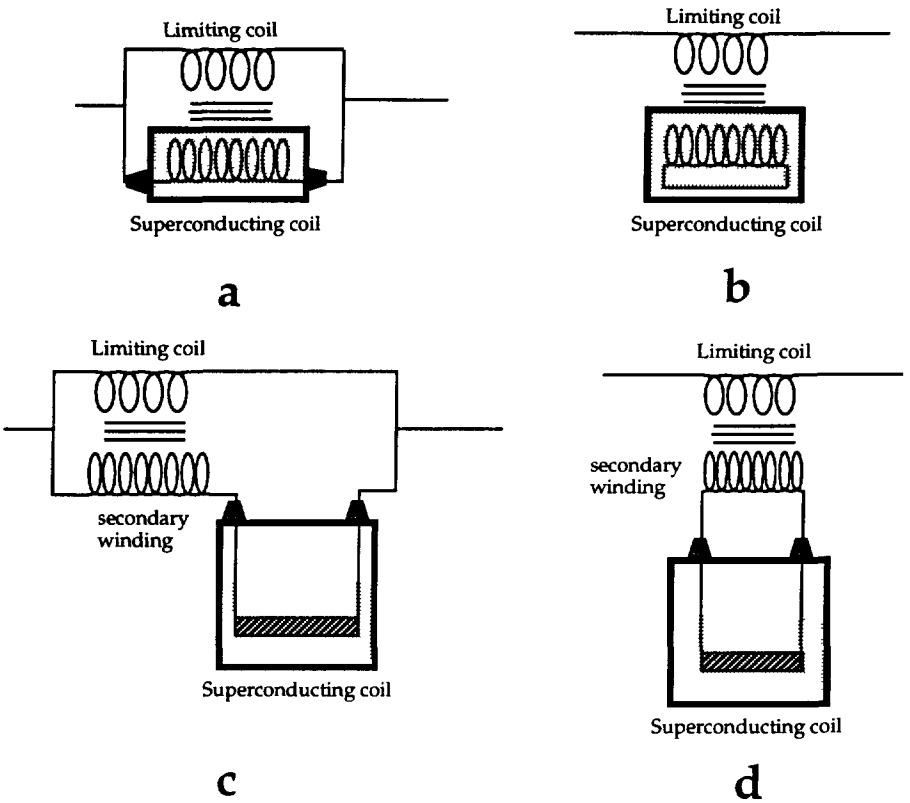
3. Our design : inductive limiter with variable coupling.

Our objective was to design a current limiting device with a reduced current through the superconducting coil compared to the line current. With such a design the superconducting cable is simple, it solves the nowadays difficulties already mentioned, the cryogenic losses are

reduced and the linear resistance is high. The basic idea is the use of a series transformer consisting of two magnetically coupled windings with a different turn numbers. The ratio for the currents is in the ratio of the turn numbers.

The primary winding is put in series in the line to protect and it is advantageously in copper. If it is superconducting it is designed so that it does not quench during a fault. The secondary winding must be superconducting (internal cryogeny) or connected in series with a superconducting coil with a low self inductance (external cryogeny). The external cryogeny is a most simpler solution from cryogenic point of view. The internal cryogeny requires non metallic tightness cryostats with a complicated shape.

In this design the superconducting coil triggers the limitation by quenching but the limitation is accomplished by the primary self inductance : this limiter is an inductive one. In order to reduce the current through the superconducting coil the turn number for the secondary is higher than for the primary. The inductive voltage drop under normal operation is limited by the good magnetic coupling between the two windings. Figure 1 shows several possible schemes. Appendix A gathers some formula in normal operation for the solutions with external cryogeny (1c and 1d). For the parallel connections (1a and 1c) the primary and secondary windings have to be wound in opposition ($M < 0$) to decrease the inductive voltage drop under normal operation.



L_p : primary self inductance L_s : secondary self inductance M : primary secondary mutual inductance

$$k = \frac{|M|}{\sqrt{L_p L_s}} \text{ (coupling coefficient)}$$

Fig. 1. — Several configurations for limiters with a series transformer. 1a, 1b : internal cryogeny. 1c, 1d : external cryogeny.

Overvoltages appear for the external cryogeny solutions under limitation operation with the same values for the two solutions (1c and 1d) considering an identical ratio of superconducting current to the line current. These overvoltages in addition to the dielectric stresses, lead to thermal stresses for the superconducting coil.

The internal cryogenic solutions do not present overvoltages if the superconducting coil quenches in mass but it is an ideal case and overvoltages appear across the resistive part of the superconducting coil at least at the beginning of the quench. The thermal stresses remain. The current density through the superconducting coil under fault conditions is the same for external and internal cryogeny solutions and amounts to :

- solution 1b or 1d :

$$J_{sc} = \frac{I_{sc}}{S} \approx \frac{V \dfrac{|M|}{L_p}}{SR} = V \frac{k \sqrt{\dfrac{L_s}{L_p}}}{\rho L} \approx V \frac{k \dfrac{N_s}{N_p}}{\rho L}$$

- solution 1a or 1c :

$$J_{sc} = \frac{I_{sc}}{S} \approx \frac{1 - \dfrac{M}{L_p}}{SR} V = V \frac{1 \pm k \sqrt{\dfrac{L_s}{L_p}}}{\rho L} \approx V \frac{1 \pm k \dfrac{N_s}{N_p}}{\rho L}$$

(R : coil resistance, L : cable length, S : section, ρ : resistivity.)

The overcurrents are functions of the turn ratio, that is to say the current ratio. The length should be in the same ratio to keep the same Joule power density. These large lengths may be a problem to get a mass transition. For example, if the current in the superconducting coil is one tenth of the line current, the cable length should be then multiplied by 10. We will see below that the superconducting volume is kept the same compared to the resistive limiter.

To reduce the thermal stresses on the superconducting coil, we have proposed a device with a variable coupling. The primary and secondary windings must be well coupled under normal operation ($k \approx 1$, for a low normal voltage drop) and decoupled ($k \to 0$) under fault conditions (for reduced thermal stresses on the superconducting coil).

The variation of the coupling coefficient is accomplished by the saturation of a magnetic circuit. The magnetic core is not saturated under normal operation as the voltage across the primary winding is low (normal voltage drop). On the contrary, under fault conditions, the magnetic circuit saturates itself naturally as the voltage is high across the limiter : this voltage is equal to the phase to ground voltage if the source impedance is neglected.

The decoupling reduces the amount of superconducting material compared to the resistive device. The length of the superconducting coil is defined by protection considerations against excessive temperature rises. To give some comparisons we have assumed adiabatic conditions and a mass quench for the coil. The relations between the superconducting volume ϑ_{sc} in our designs and the superconducting volume ϑ_0 for the resistive limiter are (see Appendix B) :

- parallel connection :

$$\vartheta_{sc} = \frac{1 + k_d \sqrt{\dfrac{L_s}{L_p}}}{1 + \sqrt{\dfrac{L_s}{L_p}}} \vartheta_0 \qquad k_d = \left(\frac{|M|}{\sqrt{L_p L_s}} \right)_{\text{under fault}}$$

- short circuited secondary :

$$\vartheta_{sc} = k_d \, \vartheta_0 \, .$$

Without decoupling ($k_d = 1$) the superconducting volume remains the same.

The two connections (parallel and short circuit) have been both studied. The parallel connection decreases the voltage drop but increases the thermal stresses and the superconducting volume even if assuming a same ratio of superconducting current to line current (see Tab. VI). The gain for the apparent inductance (overall inductance under normal operation) decreases when the turn ratio increases so that the short circuit connection would be kept preferentially.

Table I. — *Comparison between our design and the resistive limiter.*

	Resistive	Our design
Normal voltage drop	very low	higher
Failing characteristic	not safe	moderately safe
Overvoltages	no	high
Superconducting cable	high current capacity	simple reduced current
Cryogenic losses	reasonable	lower
Weight and volume	low	high
Recovery	slow	less slow
Superconducting volume	reasonable	lower
Limitation current	reduced	higher

If the superconducting coil quenches accidentally under normal conditions the load may be supplied if a circuit breaker isolates quickly the superconducting coil. The operation is reduced but the continuous supply may be performed even if the saturated magnetic circuit introduces a lot of harmonics. The resistive limiting device does not present this relatively fail safe characteristic : it insures the opening of the line in case of an accidental quench. The experimental curves (Fig. 2) get with our model (see below) illustrate this operation. The

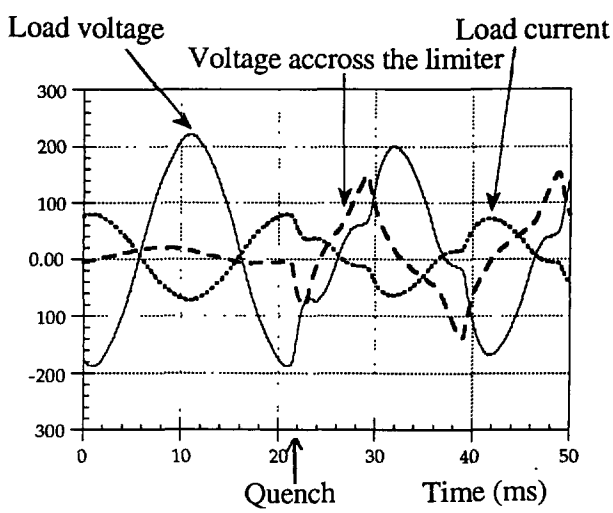


Fig. 2. — No fault operation under quench conditions.

quench has been initiated by a heater under the superconducting strand. The current and the voltage for the resistive load are distorted but their r.m.s. values are not reduced too much.

Table I summarizes some compared characteristics between the resistive limiter and our conception.

4. Model.

To validate experimentally our conception a model limiter has been designed, manufactured and tested (Tab. II). The overall cryogenic losses brought back to room temperature taking into account the efficiency of a liquefier (1/3 000) amount to 240 W. The device has low harmonic generation under normal operation. Due to the current distribution (3 : 1) the parallel connection has been kept to reduce the normal voltage drop.

Table II. — *Model characteristics.*

Rated voltage	150 V_{rms}
Rated line current	50 A_{rms}
Frequency	50 Hz
Short circuit current (without device)	1400 A_{peak} (20 I_n)
Limitation current (asymmetrical fault)	280 A_{peak}
Normal inductive voltage drop	4.6 % V_n
Current sharing	$I_p / I_s = 3$
"Classical" losses iron/copper	20 W / 260 W
Total cryogenic losses ($\zeta = 3000$)	80 mW (240 W)
(cryostat / leads & support / coil)	(30 / 45 / < 5)

Analytical and numerical calculations using finite element programs developed by the LEG and Cedrat Recherche [7] has made it possible to design the magnetic circuit (Fig. 3) and to find compromises between a reduced voltage drop, an effective limitation and an important decoupling under fault conditions. The agreement between experimental results and calculations is correct for all the parameters. The decoupling coefficient k_d is equal to 0.6.

The superconducting coil (Tab. III) is wound on a fiber glass epoxy support which is immersed directly into a standard 100 liter helium tank. The coil consists of two concentric solenoids connected in series.

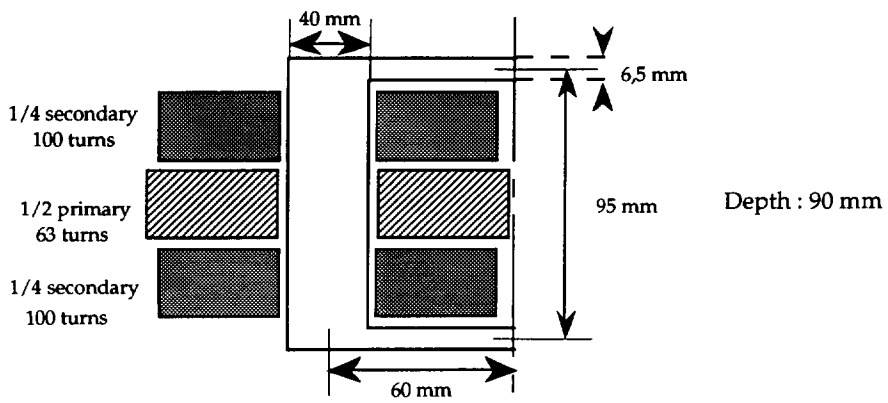


Fig. 3. — Magnetic circuit scheme.

Table III. — *Superconducting coil characteristics.*

Superconducting coil		Superconducting conductor	
Number of layer in series	2	Type	single strand
Number of turn / layer	350	Diameter	0.2 mm
Diameter / Height	35 mm / 80 mm	Number of filaments	377 982
Self inductance	280 µH	Diameter of the filaments	0.139 µm
Critical current	60 A_{peak}	Twist pitch	1 mm
Resistance	800 Ω	% NbTi - % CuNi - % Cu	18.7 - 81.3 - 0

Figure 4 gives the electrical circuit for the tests. The short circuits are made through the circuit breaker C_1. The circuit breaker C_2 opens after the quench with a variable delay to protect the superconducting coil and to make it recover. This circuit breaker may close itself after another delay (some tenth of ms to several seconds) to provide operating sequences (for example twice opening : O-C-O duties (Opening-Closing-Opening)). Some tests have been performed without the superconducting coil ; limitation is not effective at all as the fault current may reach 700 A_{peak}.

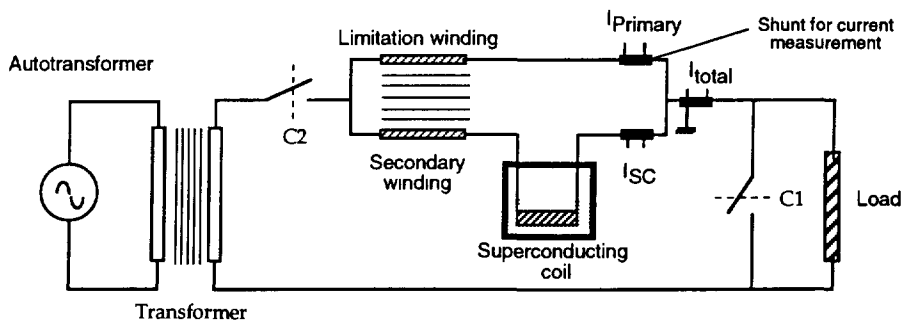


Fig. 4. — Electrical circuit for the tests.

Asymmetrical faults (Fig. 5, fault at zero of voltage) and symmetrical (fault at peak of voltage) have been performed. After the short circuit the current rises very quickly up to the superconducting coil quenches by overstepping its critical current (60 A). The corresponding line current value (250 A) is the threshold current of the limiter. Afterwards due to the rapid growth of the resistance at the secondary circuit all the current is diverted to the primary winding which limits by its self inductance. Due to the high resistance at the secondary circuit the decrement to a symmetrical wave form is rapid and the fault current is limited to 280 A_{peak} for the first alternance and to 220 A_{peak} for the following alternances. The voltage across the superconducting coil reaches 1 400 V when the quench occurs ; this overvoltage is due to the inductance of the source. Afterwards the voltage is distorted with high maximum values : 870 V. These values are to be linked to the ratio of the turns. Decoupling by saturation has no influence on the maximum values of the voltages : in sinusoidal operation voltages and magnetic flux are in quadrature (Lentz law), when the voltages are maximum the magnetic circuit is not saturated, the winding are well coupled and the voltages are in the ratio of the turns. Ineffective to reduce dielectric stresses, the decoupling by magnetic saturation decreases nevertheless the thermal stresses on the superconducting coil as it reduces the r.m.s. secondary

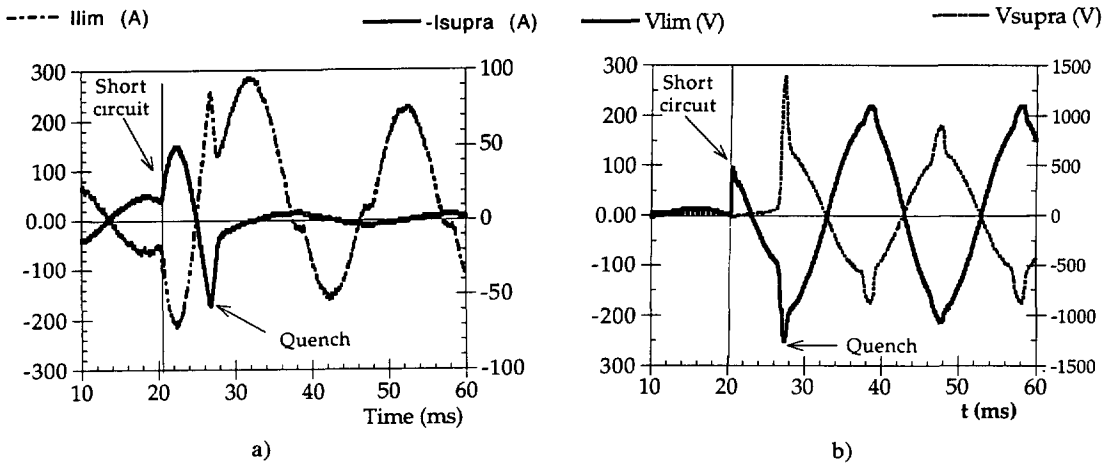


Fig. 5. — Asymmetrical test, test conditions : $V_{source} = 150\ V_{rms}$, $I_{line} = 50\ A_{rms}$ (before fault), $I_c = 60\ A_{peak}$, $Z_{source} = 0.15\ \Omega$ ($I_{cc} = 20\ I_n$). a) Current waves. b) Voltage waves.

voltage (in our case 290 V_{rms} against 475 V_{rms} without decoupling that is to say two times less energy dissipated in the superconducting wire for a same cable length).

Figure 6 gives the time evolution of the dissipated power and of the resistance for the superconducting coil. No mass quench occurs : even after 20 ms the resistance reaches only 200 Ω, 25 % of the coil. The initial apparent propagation velocity amounts 3.3 km/s. The energy dissipated in 20 ms, a sufficient delay for a circuit breaker to open, is 80 J and it corresponds to the vaporisation of 32 cm^3 of liquid helium. Some O-C-O duties have been performed. The recovery time for the superconducting coil is lower than 4 s.

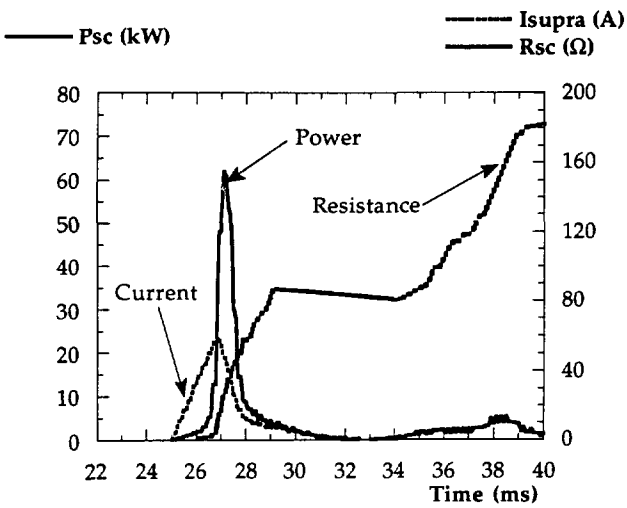


Fig. 6. — Power, resistance and current evolutions with time for the superconducting coil.

5. Extrapolation to an industrial device.

The specifications for an industrial device are given by table IV. They relate to the standard 63 kV substations of the French network. The short circuit current is the breaking capacity of the present switchgears. It could be higher (and even infinite theoretically) using a limiting device. The threshold current ($\approx 3\,I_n$) has been chosen to avoid any quenches in normal operation (current jumps due to a transformer connection for example). The limitation current could seem to be high but it is sufficient to perform a safe fault operation for the network. A recent investigation for U.S. utilities' needs about a distribution fault current limiter shows that a device limiting 20 kA fault to 10 kA, that means only one half of the short circuit current (15 kV circuit) is their primary candidate [8]. More high will be the limitation current more light will be the hybrid limiting device.

Table IV. — *Industrial device specifications.*

Rated voltage	63 kV
Rated current	1250 A_{rms}
Frequency	50 Hz
Threshold current	> 3000 A
Limitation current	5 to 6*I_n
Short circuit current	20 kA_{rms}

For the superconducting cable a (6 + 1) L conductor has been chosen. It is composed by six L strands (Tab. III) twisted around a resistive core. Its critical current is around 330 A settling the threshold value. A ratio of nine has been kept for the turn number of the primary and secondary windings. The electrical scheme is with the secondary winding short circuited by the superconducting coil (Fig. 1d).

The magnetic circuit has been optimized numerically as for the model.

To get a low self inductance the superconducting coil consists in the principle in two concentric solenoids wound in opposite direction and connected in parallel. Nevertheless to reduce the axial length the solenoids are composed by three layers connected in series with 1 000 turns each (Fig. 7). The overall length of the cable is 4 800 m. The coil self inductance is 4 mH and its normal state resistance 2.5 kΩ. Assuming a mass quench the energy reaches

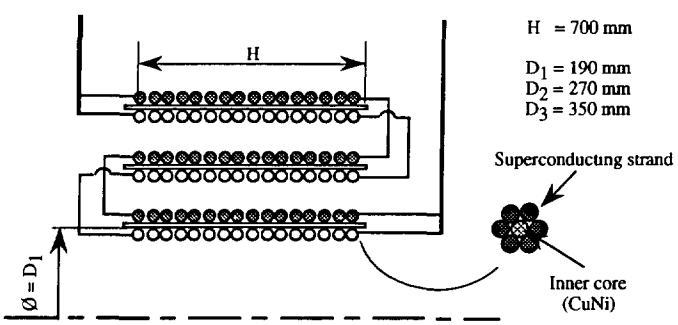


Fig. 7. — Scheme for the superconducting coil (63 kV/1 250 A).

82 kJ and vaporises 32 liters of liquid helium (daily consumption) for an opening delay of 20 ms. The temperature reaches then 90 K.

Table V gathers designs for three superconducting devices : DASC, resistive and hybrid limiters. The DASC [9, 10] corresponds to the scheme 1 b of figure 1 but without coupling variation. The resistive device has been extrapolated from data of reference [5]. The magnetic circuit makes it possible to reduce by 70 % the rms voltage through the superconducting coil ($k_d = 0.3$). The results are in agreement with the qualitative conclusions of table I : the superconducting cable is simpler and in lower quantity, the cryogenic losses reduced (factor nearly 5) for our design but with a weight much higher and with important dielectric stresses (460 kV) under limitation. The superconducting volumes are not in the ratio of $k_d(0.3)$: the threshold values are not the same and the maximum temperatures after a quench may be different too. The weight (roughly 30 tons for a three phase system) represents nevertheless only one fifth of the weight for a 63 kV/1 250 A transformer. The DASC in this version presents little interest except the absence of dielectric stresses for the superconducting coil if a mass quench occurs.

Table V. — *Comparison between* DASC, *our design and the resistive* SC *limiter.*

	Our design	DASC	resistive limiter
Rated voltage	36 kV_{rms}	36 kV_{rms}	36 kV_{rms}
Rated current	1250 A_{rms}	1250 A_{rms}	1250 A_{rms}
Frequency	50 Hz	50 Hz	50 Hz
Normal voltage drop	3.8 % V_n	14,5 % V_n (2)	1 %
Threshold current	5000 A_{peak}	5300 A_{peak}	3000 A_{peak}
Limitation current	7200 A_{peak}	5300 A_{peak}	3000 A_{peak}
Superconducting cable	"(6+1) L"	"6*(6+1)+1 L"	"6*(6+1)+1 L"
Current sharing	9:1	4:1	
Losses copper	45 kW	52 kW	0
Losses iron	1 kW		0
Losses cryogeny	2.2 kW(1)		10.5 kW
Helium daily consumption	65 l/d	750 l/d	195 l/d
Magnetic core weight	6 Tons	25 Tons	0
Copper weight	2 Tons	2,5 Tons	0
Superconducting + core weight	7.5 + 1.2 kg	65 kg	16 + 7 kg
Dimensions	5.2*5*0.5 m*m*m	3*1.5*2 m*m*m	

(1) brought back to room temperature ($\zeta_{liquefier} = 3000$; $\zeta_{refrigerator} = 700$)

(2) this value may be reduced up to 7%

Acknowledgements.

This study has been supported by the French Ministry of Research and Space.

Appendix A.

Table VI. — *Characteristic quantities for limiters with a series transformer (external cryogeny). (The sign in front of the coupling coefficient relates to the opposite sign of the mutual inductance.)*

		Short circuited secondary (Figure 1 d)	Parallel connection (Figure 1 c)
NORMAL OPERATION	Superconducting current in function of the line current	$I_{sc} = \frac{\lvert M \rvert}{L_s} I_{line}$ $= k_o \sqrt{\frac{L_p}{L_s}} I_{line}$ $= k_o \frac{N_p}{N_s} I_{line}$	$I_{sc} = \frac{1}{1 + \frac{L_s - M}{L_p - M}} I_{line}$ $= \frac{1}{1 + \sqrt{\frac{L_s}{L_p}} \frac{\sqrt{L_s} \pm k_o \sqrt{L_p}}{\sqrt{L_p} \pm k_o \sqrt{L_s}}} I_{line}$ $= \frac{1}{1 \pm \frac{N_s}{N_p}} I_{line} \quad (k_o = 1)$
	Apparent inductance L_a	$L_a = L_p\left(1 - \frac{M^2}{L_p L_s}\right)$ $= L_p\left(1 - k_o^2\right)$	$L_a = \frac{L_p\left(1 - \frac{M^2}{L_p L_s}\right)}{1 + \frac{L_p}{L_s} - 2\frac{M}{L_s}}$ $= \frac{L_p\left(1 - k_o^2\right)}{1 + \frac{L_p}{L_s} \pm 2k_o \sqrt{\frac{L_p}{L_s}}}$
FAULT OPERATION	Limiting inductance ($I_{sc} = 0$)	L_p	L_p
	Voltage across the SC coil ($I_{sc} = 0$)	$V_{sc} = V \frac{\lvert M \rvert}{L_p}$ $= V k_d \sqrt{\frac{L_s}{L_p}}$ $= V k_d \frac{N_s}{N_p}$	$V_{sc} = V\left(1 - \frac{M}{L_p}\right)$ $= V\left(1 \pm k_d \sqrt{\frac{L_s}{L_p}}\right)$ $= V\left(1 \pm k_d \frac{N_s}{N_p}\right)$

Appendix B.

Assuming adiabatic conditions and a mass quench for the superconducting coil the maximum temperature T_{max} is given by the expression :

$$(H(T_{max}) - H(T_0))\,\vartheta_{sc} = \frac{1}{R}\int_0^{\Delta t} v_{sc}^2\,dt \quad \begin{cases} H : & \text{enthalpy} \\ \vartheta_{sc} . & \text{superconducting volume} \\ v_{sc} . & \text{voltage across the coil} \\ R : & \text{coil resistance} \\ \Delta t : & \text{time delay before opening} \\ T_0 : & \text{initial temperature (bath temperature)} . \end{cases}$$

One may deduce the necessary length of the superconducting coil L_{sc} .

$$L_{sc} = \sqrt{\frac{1}{\rho\,\Delta H}}\sqrt{\int_0^{\Delta t} v_{sc}^2\,dt} \quad \begin{cases} \rho : \text{resistivity} \\ \Delta H = H(T_{max}) - H(T_0) . \end{cases}$$

This length does not depend upon the superconducting cable section. The expression of the superconducting volume is :

$$\vartheta_{sc} = \frac{I_{sc}}{j_{sc}}\sqrt{\frac{1}{\rho\,\Delta H}}\sqrt{\int_0^{\Delta t} v_{sc}^2\,dt} \quad \begin{cases} I_{sc} . & \text{superconducting current} \\ j_{sc} . & \text{current density} . \end{cases}$$

The superconducting volume for a resistive limiter (same voltage and current) is expressed by :

$$\vartheta_0 = \frac{I_{\text{ligne}}}{j_{sc}}\sqrt{\frac{1}{\rho\,\Delta H}}\sqrt{\int_0^{\Delta t} v_{sc}^2\,dt} .$$

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