A HIGH-POWER MAGNETICALLY SWITCHED SUPERCONDUCTING RECTIFIER OPERATING AT 5 Hz *

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Abstract

Above a certain current level, the use of a superconducting rectifier as a cryogenic current source offers advantages compared to the use of a power supply at room temperature which requires large current feedthroughs into the cryostat. In some cases, the power of such a rectifier is immaterial, for example if it is to be used as a current supply for short test samples with low inductances. Usually, however, a rectifier is intended to energize large superconducting magnets, so the maximum power available becomes an important parameter since it determines the loading time. One method of increasing the power of a rectifier is to raise the operating frequency. In this respect, magnetically controlled switches with very fast switching times are preferable to thermally controlled ones.

This paper reports on the design, as well as the experimental results, of a magnetically switched full-wave superconducting rectifier. Once this rectifier is brought to its design frequency of 5 Hz, the average power delivered to the cryogenic load will be 500 W.

Introduction

In the past few years, several superconducting rectifiers were built and tested at the University of Twente (references 1, 2 and 3). They performed very well and demonstrated that superconducting coils for 9 and 25 kA can be energized with an efficiency exceeding 96 %. However, the operating frequency was limited to below 0.1 Hz due to the application of thermally controlled switches with large activation and recovery times. An alternative was presented in Ref. 4, a magnetically controlled switch that was successfully tested up to 25 Hz. Similar magnetic switches were used in the 500 W, 1 kA rectifier described here. For this rectifier the operating frequency is substantially higher than 0.1 Hz and it is in fact not determined by the cryogenic part of the system but merely by the power of the room-temperature supplies used to drive the primary of the transformer and the control coils of the switches.

The principle of a full-wave superconducting rectifier with inductive commutation of the secondary current is explained in figure 1. A primary current with an amplitude of $\hat{I}_p$ will generate a secondary current through the load that will increase step-wise to a maximum I_{max}. Each half period of the primary waveform is made up of four parts:

1) pumping part, where a primary current step causes an increase of the secondary current.
2) delay time, where the primary current is constant, allowing one of the switches to be closed.
3) commutation part, where a primary current step causes the current in one half of the secondary circuit to be transferred to the other half.
4) delay time, allowing one of the switches to be closed.

By reversing the sequence of the control signals, pumping down, i.e. decreasing the load current is also possible. The magnitude of the commutation step obviously depends on the momentary secondary current which must therefore be measured in order to generate the correct primary current. For a detailed theoretical treatment of superconducting rectifiers the reader is referred to Ref. 1. Here we confine ourselves to the mean power of a rectifier with constant frequency :

$$\bar{P}_L = \alpha f k^2 \left(\tfrac{1}{2} L_p \hat{I}_p^2\right)$$

$$\alpha = 4 \left(I_L / I_{max} \right)^2 / \ln \left(I_{max} / (I_{max} - I_L) \right)$$

$$I_{max} = 2 \hat{I}_p k \sqrt{L_p / L_{sec}}$$

L_p, L_{sec}	primary and secondary transformer inductance.
k	coupling constant of the transformer.
f	operating frequency of the rectifier.
I_L	load current after a completed loading cycle.

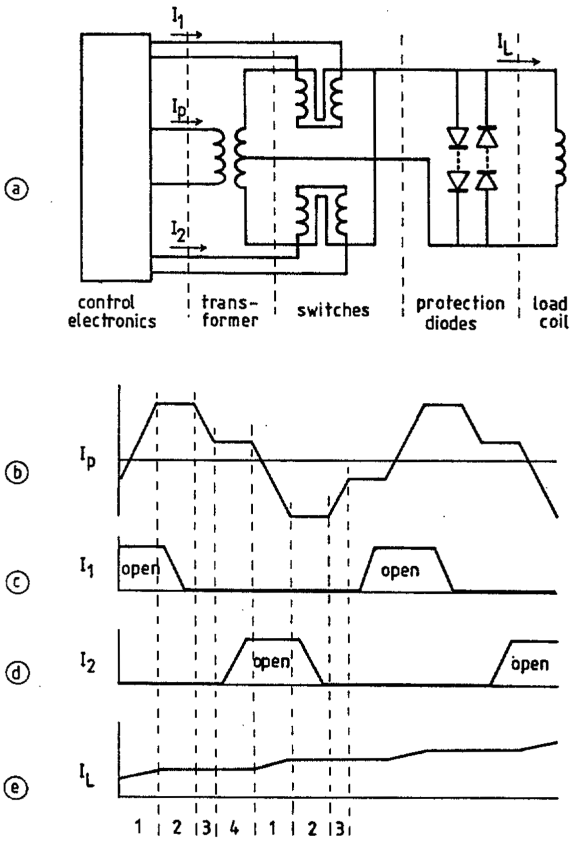

Fig. 1 a) Circuit of the rectifier system.
b) Transformer primary current.
c) Current in control coil 1.
d) Current in control coil 2.
e) Current through the load.

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The factor α reaches a maximum of 1.6 when the current through the magnet is increased to 71.5 % of I_{max}. For a given primary energy of the transformer the mean power can only be increased by improving the coupling constant of the transformer or by raising the frequency.

An experimental rectifier

In order to demonstrate the feasibility of high-frequency magnetically switched rectifiers, we designed an experimental model, of which the construction was completed a few months ago. Design parameters for this rectifier were a primary and secondary current of 30 A and 1000 A respectively, an operating frequency of about 5 Hz, an average power of 500 W. The cryogenic part of the rectifier, mounted in a 0.27 m diameter cryostat, is shown in figure 2. Subsequently, some aspects of this particular rectifier will be discussed.

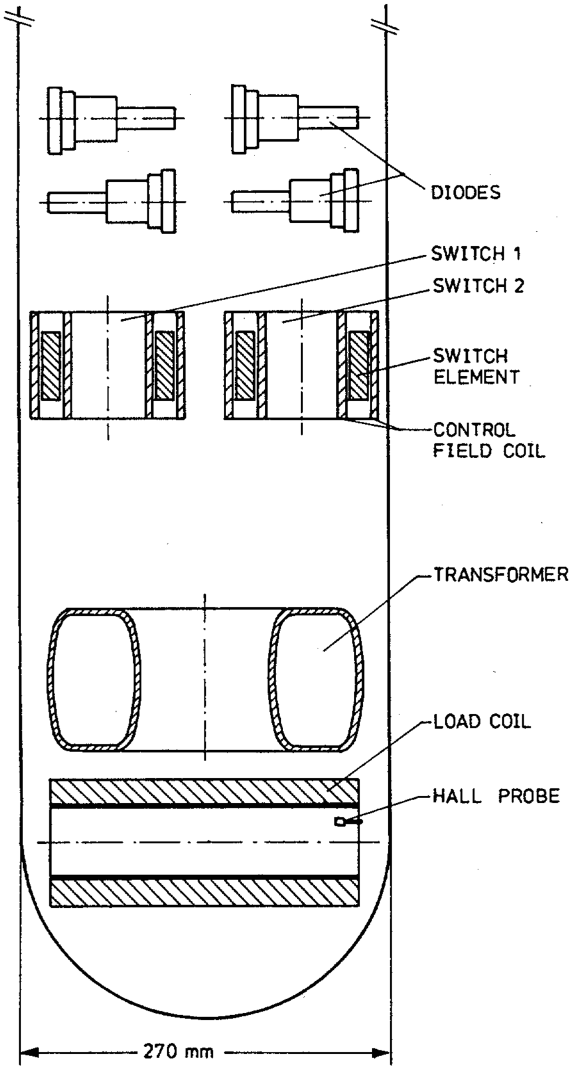

Fig. 2 Cross-sectional view of the rectifier mounted in a 0.27 m diameter cryostat.

The switches

The magnetic switches consist of a switching element placed between an inner and outer control coil having opposite windings. With this geometry a combination of a homogeneous field at the switch element and a control coil with low self-inductance is obtained. The switch elements are made of 24 parallel strands of multifilamentary wire with a second critical field of 0.8 T (MCA, Nb1%Zr/CuNi, 0.3 mm dia., 574 filaments). Part of our investigations is to compare switch 1 and 2 which differ in the arrangement of these 24 strands (see figure 3). In the first switch 48 strands were wound as a flat cable in several layers. For the second switch 24 strands were first cabled and then two cables were simultaneously wound. The directions of transport current indicated in figure 3 show how the strands were connected afterwards in order to obtain a non-inductive switch element. A non-inductive arrangement is necessary in order to minimize the self-field of the switch element and so avoiding a serious degradation of the maximum current.

An obvious advantage of switch 1 is the higher filling factor of superconductor which results in a larger resistance in the normal state with a smaller switching volume (see table 1).

Table 1 Switch parameters.

	switch 1	switch 2
switch volume [litres]	0.23	0.29
open-state resistance [Ω]	0.83	0.69
control coil inductance [H]	0.16	0.21
open-state control current [A]	40	40

Both switches and their control coils are provided with heat drains in order to minimize temperature rises. Particularly during the pumping stage, when the control coil is energized and the momentary dissipation in the switch element can be as high as 50 W, it is important that the control coil remains superconducting. Furthermore, the switch element itself must not heat up otherwise a combination of thermal and magnetic switching would occur.

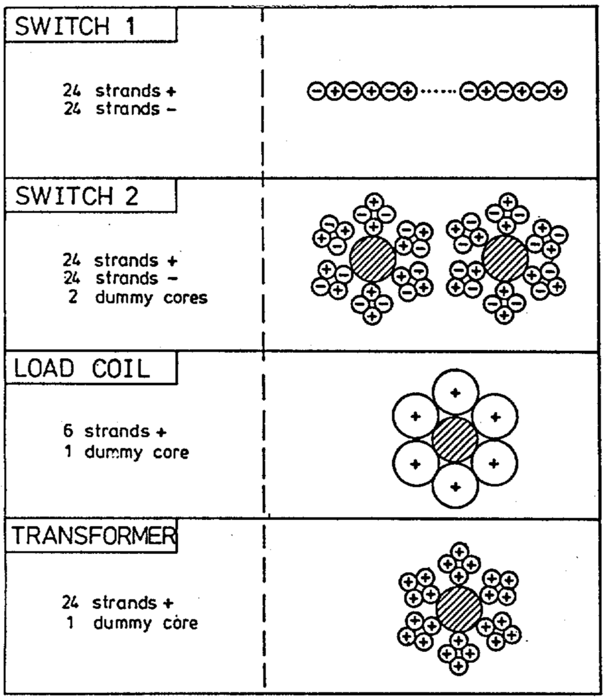

Fig. 3 Conductor geometries in the switches, load coil and transformer.

The load coil

The load coil is wet-wound with a six-strand cable on a stainless steel coil former using STYCAST 2850 FT resin. A maximum coil current of 1200 A is expected from previous critical current measurements on a single strand (MCA, NbTi/Cu, 0.686 mm dia., 2070 filaments). At the design current of 1 kA the solenoid generates a field of 4.5 tesla corresponding to a stored energy of 6.75 kJ. In the 5 cm bore and over a length of 6 cm we obtain a test-volume of 1 % homogeneity.

The positions of the rectifier components are chosen in such a way that the stray field of the load coil at the switches is less than 20 mT so that magnetic shielding of the switches is not necessary.

The transformer

The transformer is of the toroidal air-core type. This toroidal shape avoids a stray field from the transformer and magnetic coupling with all other coils in the rectifier. As a consequence, a compact construction was possible. The transformer could be mounted close to the load coil without spoiling its field homogeneity or leading to excessive mutual forces. Furthermore, the operation of the switches which are not shielded for external fields is not influenced by the presence of the transformer.

Several disadvantages of the toroidal shape compared to a solenoid were taken for granted: a) the fabrication is more difficult; b) it takes 2 to 3 times more superconducting wire to obtain a comparable self-inductance; c) the extra amount of superconductor implies larger a.c. losses; d) cooling is bad, especially at the inner side of the toroid. The latter two problems were partly overcome by realizing the primary inductance of 0.2 H with a relatively large transformer volume and few windings, resulting in a large cooling surface and moderate magnetic field. Calculations for this 0.25 m diameter transformer show a temperature rise less than 1 K if the dissipated heat due to a.c. losses at 5 Hz is conducted to the helium bath through the STYCAST impregnant and the coil windings without using heat-drains.

The secondary windings are located between two sections of primary windings in order to get a good coupling constant (>97.5 %). The primary and secondary inductances are 0.2 H and 280 μH respectively. In both transformer and control coils the same conductor was applied (MCA, NbTi/CuNi, 0.3 mm dia., 575 filaments).

Efficiency

The overall efficiency of the rectifier is defined as

$$\frac{W_L}{W_L + W_{Loss}} ,$$

where W_L is the energy delivered to the load magnet and W_{Loss} is the energy dissipated in the cryogenic environment with exception of the dissipation in the magnet itself (in our case the latter is less than 0.2 % anyway). The fraction W_{Loss} that is dissipated in the cryostat can be divided into two main contributions. First the filament hysteresis loss in all superconducting parts of the rectifier. This contribution is independant of the rectifier frequency when heating effects in the superconductor and their influence on Jc are disregarded. Based on the results of previous short sample measurements, the hysteresis loss in the rectifier was estimated (table 2). With a primary amplitude of 30 A it takes 53 periods to obtain 1000 A in the magnet. In that case the hysteresis loss is about 2.5 % of the energy in the magnet.

Table 2 Hysteresis loss contribution for I = 30 A.

two switch elements	1.9 J/period
two control field coils	0.9 J/period
transformer primary windings	0.35 J/period
transformer secondary windings	0.35 J/period

The second contribution is ohmic dissipation in the switch elements during the pumping stage. This contribution increases linearly with the frequency of the rectifier and furthermore it depends on the fraction of time of each period that is actually used for the pumping step. Therefore, the efficiency is also closely related to the mean power of the rectifier. Suppose for example that the magnet is loaded up to 1000 A with a constant frequency of 5 Hz and that 35 % of each period is used for pumping. Then, the mean power exceeds 500 W while the ohmic loss is 4 % of the magnet energy. Some additional losses such as eddy current dissipation in superconductors or construction materials are negligibly small. So, depending on frequency and primary signal, the overall efficiency of the rectifier varies from 93.5 to 97.5 %

Control electronics

A correct operation of the rectifier can be obtained with various shapes of the primary current. In the preliminary tests until now a primary signal was used with constant time intervals for the pumping stage, the commutation stage and the activation/recovery of the switches. At this moment a rectifier control unit is under construction which generates a constant primary voltage and therefore a constant current rate during the commutation and pumping stage. This choice allows for a combination of high efficiency and high average power. It also means that in general the frequency is not constant because the time intervals needed for pumping and commutation depend on the actual load current.

Another point is the power supply needed to drive the control coils and the transformer. Since the control coils are never open simultaneously it is possible to use a single power supply for both switches. This is a 40 A, 250 V amplifier with unipolar current and bipolar voltage especially suited for inductive loads. A similar amplifier with bipolar current, which is now being developed, will be used for the primary of the transformer.

Completion of the above-mentioned electronics will enable a rectifier frequency of 5 Hz.

Protection

The conductors must be protected against damage due to excessive heating after a quench anywhere in the superconducting system.

For both control coils and the primary of the transformer this protection is achieved by means of quench detectors which measure the resistive component of the supply voltage. If it exceeds a certain level, a quench is assumed and the current of the coil in question is switched off as quickly as possible.

The secondary circuit is protected against a dump of the load coil energy by means of diodes connected across the load coil terminals. More than 98 % of this energy is dissipated in the diodes above the helium level when a quench occurs in the secondary circuit while the magnet remains superconducting. On the other hand, if the magnet quenches, all the energy is dissipated in the magnet itself. In the latter case a coil current of 1 kA will decay within 1 s corresponding to a maximum temperature rise less than 100 K. Both types of a secondary quench were forced several times at a magnet current of 1 kA and were found completely safe to the rectifier.

Experimental Results

Both switches were tested in the secondary rectifier circuit with a short-circuit as a load. By opening switch 1 the maximum current of switch 2 can be measured and vice versa. These experiments are summarized in figure 4 for a sinusoidal secondary current. It should be mentioned that the cooling of the transformer is bad compared to the cooling of the switch elements so above a certain frequency we expect the maximum secondary current to be limited by the transformer. Figure 4 and previous measurements on the transformer indicate that this occurs at 5 Hz.

Depending on the supply voltage for the control coils, we measured switch-on and switch-off times between 25 and 100 ms.

The completed rectifier was tested for several values of primary amplitude, load current and frequency. The recorded load currents for pumping up and down fit the theoretical curves within 2 %. Figure 5 for example shows the primary current and load current for a run at 1.1 Hz and 60 W mean power. At 700 A a commutation error occurs causing a secundary quench. Within 3 seconds 98 % of the load energy is dissipated in the protection diodes. For reasons mentioned before the maximum frequency is limited to 2 Hz for the present.

During the tests, two types of failures were encountered. First, some quenches of the control coils occured due to a low helium level. A second failure occurs if the magnitude of the commutation step is not correct. Then, the remaining current in one half of the secondary circuit will be commutated resistively to the other half after the switch is opened. The current rate involved with a too large commutation error causes a quench in the secondary circuit.

Conclusions

Preliminary tests of the new magnetically controlled superconducting rectifier were successful. After separate tests of the components, the rectifier was assembled and used to charge a 1 kA, 6.75 kJ magnet. The rectifier reliably energizes this magnet up to 1 kA and is furthermore fully protected against damage after a quench anywhere in the system. The next step in our experiments concerns raising the mean power of the rectifier to 500 W by increasing the operating frequency from 2 Hz to 5 Hz.

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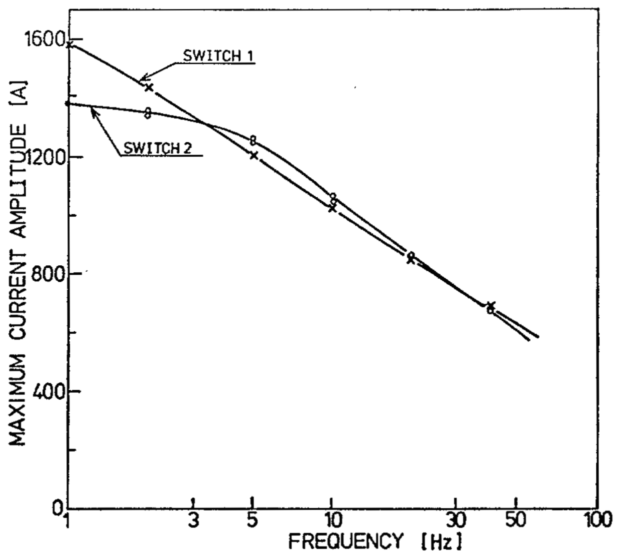

Fig. 4 Maximum sinusoidal current in both halves of the secondary circuit as a function of the frequency.

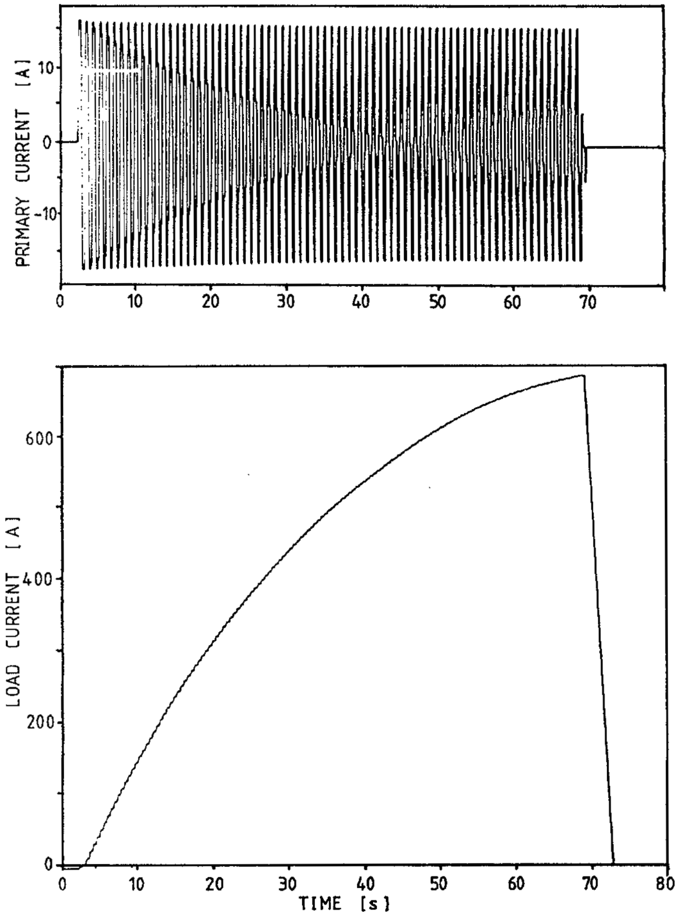

Fig. 5 Primary current and load current recorded in a run at 1.1 Hz and a mean power of 60 W.