IEEE TRANSACTIONS ON MAGNETICS, VOL. 27, NO. 2, MARCH 1991

# DEVELOPMENT OF A THERMALLY SWITCHED SUPERCONDUCTING RECTIFIER FOR 100 kA

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## Abstract

A full-wave superconducting rectifier for 100 kA has been developed at our institute. Typical design values of this device are: a secondary current of 100 kA, a primary amplitude of 20 A, an operating frequency of 0.5 Hz and an average power in the order of 100 W. The rectification is achieved by means of thermally controlled superconducting switches with recovery times of 150 to 300 ms. A description of the rectifier system is given in the paper. The first experiments, in which the rectifier was tested up to 25 kA, are discussed.

## Introduction

A superconducting rectifier is a cryogenic device that converts an AC current with moderate amplitude into a large step-wise increasing superconducting current. It can therefore be applied as a current supply for superconducting loads that require large operating currents. The advantages of such an approach become more and more obvious as the required current level increases. Firstly, for very high currents a superconducting rectifier system is less expensive than a conventional power supply. Secondly, the heat leak to the liquid helium is almost eliminated because of the small primary amplitude. This principle is known for a long time, but so far it was never applied for current levels exceeding 25 kA.[1] The new rectifier described here is designed for 100 kA and will be used for the experimental investigation of high-current superconducting cables.

Figure 1 shows the basic scheme of the rectifier, where the main components are a superconducting transformer and two superconducting switches. In our rectifier, the switches actually consist of small parts of the secondary windings that can be heated up above $T_C$ to create normal zones. Additional components not shown in the scheme are present, such as the electrical joints connecting the rectifier to its load and the sensors that measure the secondary current. A micro-computer controls the operation by supplying the correct signals for the primary and the switches. As illustrated in figure 2, this is a cyclic process where every half cycle consists of four stages:

1) Opening a switch. A heater pulse is supplied to one of the switches in order to open it.
2) Pumping. With one switch open the primary current is ramped to the amplitude $\hat{I}_P$ causing an increase $\Delta I_L$ of the current through the load. Usually, the voltage $M_{PS}dI_P/dt$ appearing across the switch is sufficient to maintain the open-state, so using the heater is neither necessary nor efficient.
3) Closing a switch. The primary current is kept constant. As a result, the voltage across the switch becomes zero and thermal recovery will occur, i.e. the switch will close.
4) Commutation. With both switches closed, the primary current is changed by an amount $\Delta I_P$, thereby causing the current in one half of the secondary circuit to be transferred to the other half. This inductive commutation step is essential in order to enable cyclic operation. Note that $\Delta I_P$ is proportional to the momentary current $I_L$ in the load, therefore $I_L$ has to be measured and fed back to the computer.

When repeating the above process the current through the load will increase in a step-wise manner, so-called "pumping up". It is also possible to "pump down" by reversing the sequence of the control signals.

Manuscript received September 24, 1990.

## Theory

The ratio of input and output current of the rectifier is roughly equal to the ratio of secondary and primary turns on the transformer. To be more precise, the maximum output current that can theoretically be generated is

$$I_{MAX} = 2\,\hat{I}_P\,k\,\sqrt{L_P/L_S}\,, \tag{1}$$

where $\hat{I}_P$ is the primary amplitude, $L_P$ and $L_S$ the self inductances of the primary and full secondary of the transformer and k the coupling constant between $L_P$ and $L_S$. The step-wise increase of $I_L$ is given by

$$I_L(n) = I_{MAX}\left[\,1 - \exp\left(-\frac{2nL_S}{L_L}\right)\right], \tag{2}$$

where n represents the number of half cycles and $L_L$ the self inductance of the load. In Eq.(2) it has been assumed that the dissipated energy in the secondary circuit is small compared to the stored energy and that $L_L >> L_S$, which is true for most rectifiers. The number of cycles required to attain a certain current $I_L$ is proportional to the self inductance of the load.

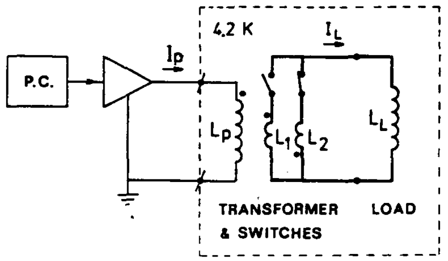

Figure 1. Basic scheme of the full-wave sc. rectifier.

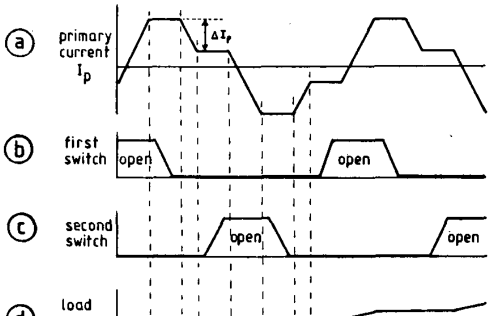

Figure 2. Diagrams explaining the operation of a full-wave rectifier with inductive commutation: a) the primary current, b) the status of switch 1, c) the status of switch 2, and d) the current through the load.

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The mean load power $P_L$ is defined as the stored energy $^1/_2 L_L I_L^2$ divided by the time required to attain $I_L$. $P_L$ depends among others on the waveform of the primary current, which is in our case defined by five parameters: the amplitude $\hat{I}_P$, the triggering time of the switches $t_T$, the recovery time $t_R$, the primary transformer voltage during the pump step $V_P$, and the voltage during commutation $V_C$. These parameters are constant during the rectifying process, resulting in the waveform shown in figure 2 with fixed current rates during the commutation and pump steps. The mean power is then equal to

$$P_L(I_L) = \frac{f_0 \; ^1/_2 L_S I_L^2}{\delta \cdot I_L/I_{MAX} - (1-\delta)\cdot \ln(1-I_L/I_{MAX})} \quad , \qquad (3)$$

with $f_0 = 1/2(t_T+t_R+t_P)$ ,

$$\delta = (t_P-t_C)/(t_T+t_R+t_P+t_C) \quad ,$$

$$t_P = 2\hat{I}_P L_P/V_P \quad \text{and} \quad t_C = 2\hat{I}_P L_P(1-k^2)/V_C \; .$$

Note that the cyclic frequency is initially $f_0$, however during operation it will either increase if $\delta>0$ or decrease if $\delta<0$. Equation (3) shows that, depending on $\delta$, an optimum value of $I_L/I_{MAX}$ exists at which the rectifier has a maximum average power. This optimum usually lies between 0.6 and 0.8.

## Design

The requirements that have to be met for this particular rectifier are: an output current of 100 kA, a primary current of 20 A, an average power of approximately 100 W and a sufficiently compact size to fit it in a 140 mm diameter cryostat. Optimum power is achieved if $I_{MAX}$ is about 140 kA. Since the coupling constant k of an air-core transformer is usually 0.8 to 0.9, it follows from Eq. (1) that $\sqrt{L_P/L_S}$ should be 4000. Therefore, a single secondary turn implies a primary coil with roughly 4000 turns. Clearly, to limit the size of the primary, the number of secondary turns should be as small as possible. In fact it was decided to use only one turn, i.e. half a turn for each part of the secondary circuit. Such a winding amounts to about 50 nH if the diameter is 120 mm. According to Eq. (3) the rectifier should then run at about 0.4 Hz in order to produce 100 W. This is an acceptable frequency in view of the expected recovery times of the switches.

To reduce the size of the rectifier the thermal switches were incorporated into the windings of the transformer. As indicated in figure 4, cooling gaps for access of helium are present between the concentric primary and secondary windings so that they are thermally decoupled. Due to these gaps k is lower than usual, namely 0.75. The required self inductance of the primary coil becomes 1.0 H, corresponding to 5000 turns if the primary is placed inside the secondary.

### The secondary conductor.

The secondary conductor has to carry 100 kA reliably. In addition it must have a high resistive CuNi matrix in order to get sufficient "off-resistance" of the switches and thus enable an acceptable rectifier efficiency. Conductors having such a high resistive matrix suffer from unstable behaviour at low magnetic fields, say below 2 T, where the current density is high. In that case the quench current reproduces poorly and it can be significantly lower than the critical current. This undesirable effect grows worse when large numbers of strands are cabled [2] and it makes accurate prediction of the maximum current of the superconducting switches impossible.

Table 1 gives the data of the applied switch conductor. Below 0.5 T, which is the maximum field at the secondary winding, the quench current varies between 200 and 400 A. This suggests that 500 strands in parallel would be sufficient to attain 100 kA. However, it was established previously [2] that when cables having a CuNi matrix are used at such a high current level, the quench current may drop to about 30 % of $I_C$. This means that in order to obtain reliable operation the conductor has to be largely over-dimensioned. It was decided to use 1610 strands instead of 500.

### The switches.

At the switches, a heater element is in thermal contact with the secondary conductor. Conductor and heater are thermally insulated from the helium bath by means of an insulation layer. The thickness $d_{INS}$ of this layer determines to a large extent the properties of the switch. If $d_{INS}$ is large, thermal recovery will be a slow process which reduces the attainable frequency and thus the power of the rectifier. If on the contrary $d_{INS}$ is small, a relatively large heat input will be required to keep the switch in the resistive state during the pump step and this will result in a poor rectifier efficiency. As a compromise we used a 2 mm thick laminate of glass fibre and epoxy.

During a pump step, the resistive state is maintained by the constant voltage $V_S = M_{PS} dI_P/dt$ appearing across the switch. Under these conditions, a stationary normal zone will develop of which the temperature distribution along the conductor can be calculated using the theory of cold end recovery[3]. Using the insulation thickness of 2 mm it was calculated that for $V_S$ larger than 4 mV, the length of the normal zone and thus its resistance is proportional to $V_S$. For example, at the expected secondary voltage of 10 mV the normal length is 8 mm and the switch resistance is 0.034 mΩ. The leakage current through the switch does not depend on $V_S$ and it is equal to the minimum propagation current of the 1610 parallel strands, i.e. 290 A. The maximum temperature of the normal zone is 11.3 K and is also independent of $V_S$.

If $V_S$ is reduced to below 4 mV, the ohmic dissipation in the switch is insufficient to maintain the open state. The normal region will shrink and eventually dissapear. In such a case the heater must be used during the pump step.

Table 1. Specifications of the conductors.

| applied in | primary | secondary | DC output |
|---|---|---|---|
| manufacturer | IMI | ALSTHOM | IMI |
| material | NbTi/Cu | NbTi/CuNi | NbTi/Cu |
| bare dimensions | 0.33 mm ϕ | 0.30 mm ϕ | 1.8x3.6 $mm^2$ |
| filaments | 60 | 151 | 2263 |
| η (=s.c./total) | 0.50 | 0.62 | 0.36 |

## Construction of the rectifier.

Figure 3 gives an impression of the cryogenic part of the rectifier system. The primary transformer coil, which is not shown, can be inserted from the top into both secondaries. A similar arrangement was used by Homer et al.[4]

The primary coil. The primary coil is wet-wound using Stycast 2850 FT epoxy. It is a solenoid with 5005 turns over a length of 168 mm. The inner and outer diameters are 85.5 and 96.7 mm respectively and the self inductance is 0.95 H. Table 1 summarizes the data of the applied conductor.

The secondary coils. The secondary conductor consists of 230 seven-strands twisted cables that are distributed equispaced around the circumference of the transformer. The 230 inner cables make a 11/23 turn around the primary coil whereas the outer cables are wound as a 12/23 turn in the opposite direction. At the ends, groups of 10 inner and 10 outer cables are collected and soldered onto a monolitic conductor using a 6 cm long joint. Each joint in fact corresponds to 1/23 of the DC output of the rectifier. The 23 monoliths from each end are soldered into 20 cm long copper blocks which form the main connections to the load. Thus, all 1610 wires are connected in parallel.

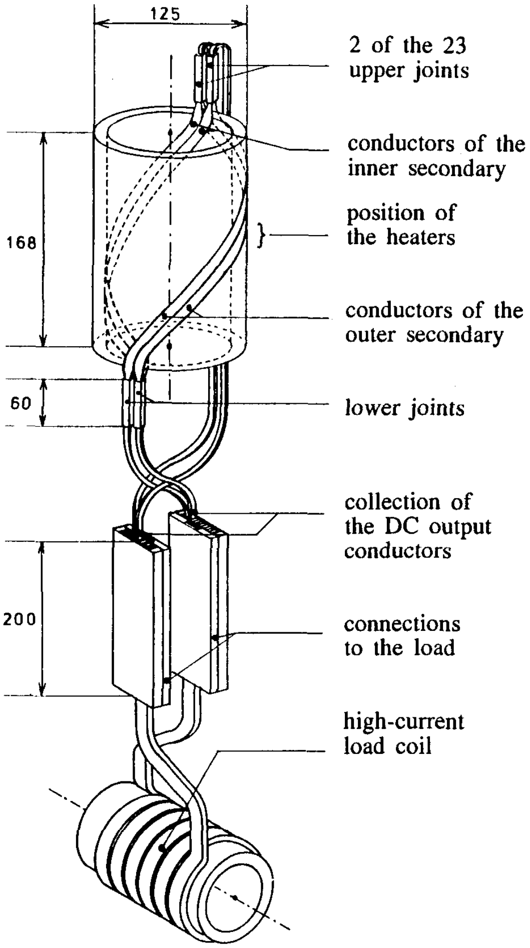


Figure 3. Schematic view of the rectifier. For clarity, only 2 of the 23 parallel secondary circuits are shown.

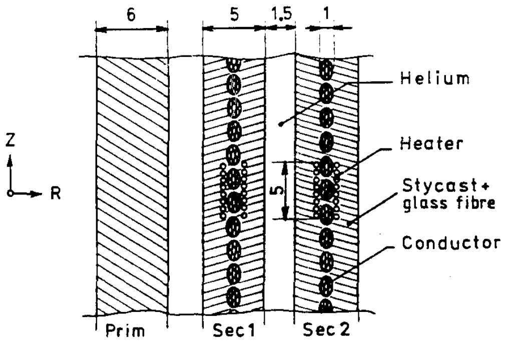


Figure 4. Cross-section of the transformer at the location of the switches.

The switches. Figure 4 shows a cross-section of the thermal switches. The heater elements consist of several turns of a manganin wire over a width of about 5 mm. These heaters are located on both sides of the conductor to ensure a rapid transition from the superconducting to the normal state when a trigger pulse is applied. The 2 mm thick layers of glass fibre and Stycast epoxy provide the necessary thermal insulation and mechanical fixation of the conductor.

The load coil. A suitable sc. load for 100 kA was not available at the early test stage. Instead, we have fabricated a 6-turn solenoid using an existing Rutherford cable. Its self inductance is 2.8 μH and the expected critical current is at least 25 kA, corresponding to a stored energy of 880 J. The load is connected to the rectifier by means of the 20 cm long soldered joints shown in figure 3.

## Results & Discussion

### Without load

A number of characteristics of the rectifier can be investigated without the presence of a load. For example, all inductances of the transformer were measured. It was found that k=0.75, $L_P$=0.95 H and $L_S$=57 nH. The mutual inductance of the primary with the inner and outer secondary windings is 82 and 93 μH respectively. This all agrees within a few per cent with the calculated values. It should be noted that $L_S$ is not quite constant but depends on the current distribution in the conductors. As a result, the current amplification of the transformer, i.e. $M_{PS}/L_S$, will drop a few per cent when the secondary current increases during the rectifiying process.

The recovery times of the switches were measured as follows. First, one of the switches is triggered and the primary current is ramped in order to create a stationary normal zone in the switch. Then, the primary current is kept constant for a time Δt to enable thermal recovery. Next, the primary current is ramped again and the secondary current is measured until a quench occurs. This in fact simulates the respective pump and commutation steps of a rectifier. Figure 5 shows the results when Δt is varied. After 150 ms, the switch has just recovered and another 150 ms later the maximum current has increased to 50 kA. The required trigger pulse was about 20 W during 100 s.

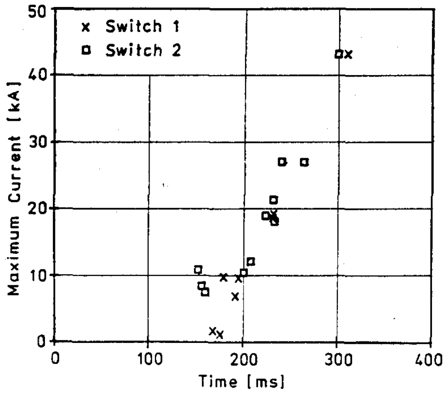


Figure 5. Maximum current of the switches versus recovery time.

The maximum current of the short-circuited secondary windings of the transformer was measured by ramping the primary current while both switches are closed. The result is a quench at 50 to 70 kA depending on the ramp rate, as can be seen in figure 6. The discrepancy between these values and the design current of 100 kA is not yet fully clear. As mentioned before, significant degradation of the maximum current can occur when cabling a large number of strands with CuNi matrix, however this effect was already taken into account in the design. Another reason can be an inhomogeneous distribution of current over the 1610 strands because the inductances and resistances of the secondary turns are insufficiently equal. Note that the quench current measured in this experiment is not necessarily equal to the maximum current of the rectifier, since the current distribution may be different.

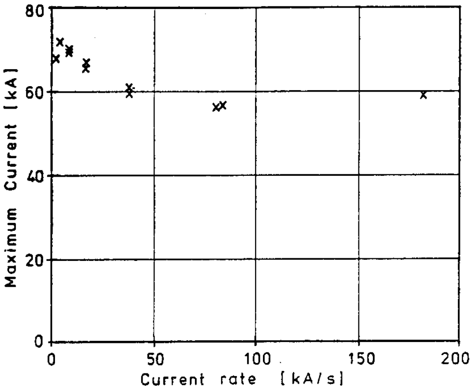
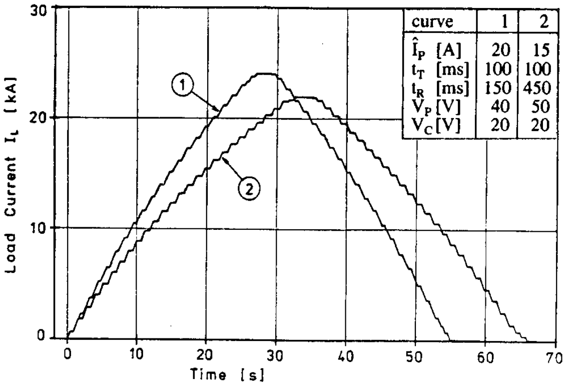


Figure 6. The maximum current of the secondary circuit as a function of the ramp rate $dI_S/dt$.

With 25 kA load coil

In a second experiment the rectifier was used to charge and uncharge the 25 kA superconducting coil. Obviously, the maximum output current is then limited by the load to 25 kA, so that optimum performance of the rectifier is not possible. Nevertheless, at a rectifier frequency of 0.4 Hz the coil was fully energized within 30 seconds, corresponding to an average power of 30 W. Figure 7 shows two load curves with the typical step-wise increase and decrease of $I_L$. When pumping is stopped $I_L$ decays with a time constant of 750 s corresponding to a total secondary resistance of 3.7 nΩ.



| curve | 1 | 2 |
|---|---|---|
| $\hat{I}_P$ [A] | 20 | 15 |
| $t_T$ [ms] | 100 | 100 |
| $t_R$ [ms] | 150 | 450 |
| $V_P$ [V] | 40 | 50 |
| $V_C$ [V] | 20 | 20 |

Figure 7. Two experimental load curves obtained using a 25 kA load coil.

The experiments demonstrate that the rectifier system is safe against quenches. This can be explained by the fact that the stored energy in the system is relatively small, less than 1 kJ. Secondly, the normal zone propagation in the switch conductor is extremely fast because a large number of short strands were connected in parallel.[5]

## Conclusions

A superconducting rectifier for high output current has been developed. The maximum current that can theoretically be produced by the rectifier exceeds 100 kA, at a primary current of 20 A. Despite this high current level, a compact lay-out was possible because 1) the thermally controlled switches were incorporated within the secondary windings of the transformer, and 2) the secondary coils consist of only half a turn each.

The first tests demonstrate a reliable and fail-safe operation of the rectifier at lower current levels. It was for example successfully used to load and unload a 25 kA coil, at a rectifier frequency of 0.4 Hz and an average power of 30 W. During tests without any load it was found that the secondary circuit of the transformer quenches at an unexpected low value of about 60 kA. Therefore, it is unlikely that the rectifier in its present configuration will attain 100 kA. The reason for this needs to be investigated. In the near future, a more detailed analysis of the performance and efficiency will be carried out.

## Acknowledgements

These investigations in the programme of the Foundation for Fundamental Research on Matter (FOM) has been supported by the Netherlands Technology Foundation (STW). The authors wish to thank Richard Volgelzang who performed an important task in the design as well as the construction of the rectifier.

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