

A THERMALLY SWITCHED 9 kA SUPERCONDUCTING RECTIFIER FLUXPUMP

Herman H.J. ten Kate, Paul B. Bunk, Harry A. Steffens and

Louis J.M. van de Klundert

Abstract - The feasibility of superconducting rectifier-fluxpumps has to be demonstrated at current levels of 10 - 100 kA, where is asked for in the superconducting devices now being planned. An intensive program has been started at the low temperature division of the University of Twente to construct such high current rectifiers. A thermally switched 9 kA full wave rectifier-fluxpump will be presented. The s.c. rectifier consists of a current step up transformer, two reliable thermally activated switches and a dummy load inductor. Both, load coil and rectifier are fully protected against failure modes. The rectifier is now (March, 1981) under test and has energized yet the load coil to a level of 4.5 kJ at 9 kA within 150 seconds, frequency 0.11 Hz, mean power 30 W, the efficiency of the energy conversion is 99,1%.

INTRODUCTION

A superconducting rectifier fluxpump is a high current, low voltage cryogenic power supply, with a potentially high efficiency, for energizing superconducting inductive loads such as magnet systems or testbeds. With such a device the heatleaks and power consumption associated with high current feedthroughs can be reduced substantially because a fluxpump is controlled only by relatively small currents. If in absence of alternatives these current feedthroughs are still required for quench protection they can be designed considerably smaller. Anyhow, it is important at this moment to investigate whether or not superconducting rectifiers could be an alternative to the common solutions. The different fluxpump designs have already been reviewed [1]. This review handles all known fluxpump designs and gives a complete introduction to the subject. It contains also a nearly complete list of references. As a result of this study further research at our laboratory will in first instance concern the superconducting full wave transformer rectifiers. Two preliminary thermally and magnetically switched low frequency rectifiers as well as a 50 Hz rectifier were built and tested [2]. The largest current generated with a low frequency magnetically switched s.c. rectifier is 8 kA [3]. This paper describes a thermally switched 9 kA full wave rectifier now being under test. Successively, the design aspects, construction details, control systems and results will come up for discussion.

PRINCIPLES AND THEORY

The s.c. rectifier consists of a current step up transformer and two reliable s.c. switches arranged as a full wave rectifier (fig. 1a). The rectifier energizes an inductor to the desired current level. A s.c. protection switch connected between the rectifier and the load coil and a dump resistor connected in parallel to the load coil, secures the rectifier against damage in case of failure modes. During normal operation the

Work supported by the Foundation for Fundamental Research on Matter, Utrecht, The Netherlands. The authors are with Twente University of Technology, Department of Applied Physics, P.O. Box 217, 7500 AE ENSCHEDE, The Netherlands.

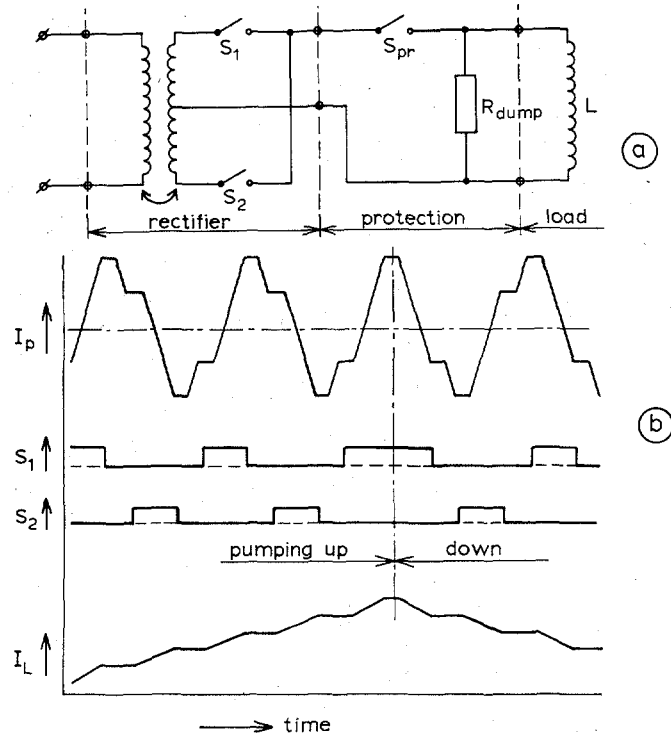


Fig. 1. Scheme of a superconducting rectifier (a) with control signals (b).

protection switch ($S_{pr.}$) and at least one of the rectifier switches (S_1 or S_2) are closed. Figure 1b shows the waveform of the primary current and the state of the rectifier switches in coherence with the ideally shaped load current I_L when charging and discharging the load. The commutation step $\delta I(t) \sim I_L(t)$ cancels, if S_1 and S_2 are closed, the already pumped current I_L exactly in the switch to be opened. As a consequence I_L runs continuously through the load and one of the two rectifier switches without producing commutation losses and so avoiding exceptional great rates of current change.

The rectifier is designed for $I_L = 10$ kA. This current has to be reached within the shortest charging time i.e. with maximum mean power and with optimal use of the transformer power supply (100 V, 22 A). The theoretical behaviour of the rectifier follows the expressions below provided that $f\ell_{sec} \ll R_d$:

$$\begin{aligned} \text{load voltage } \bar{V}_L &= f \cdot 2I_p M \left(1 - \frac{I_L}{2I_p} \cdot \frac{\ell_{sec}}{M}\right) & V; \\ \text{load curve } I_L &= \frac{2I_p M}{\ell_{sec}} (1 - \exp[-\frac{f\ell_{sec}}{L} \cdot t]) & A; \\ \text{mean power } \bar{P}_L &= \frac{1}{2} f I_L^2 \ell_{sec} / \ln(1 - \frac{I_L \ell_{sec}}{2I_p M})^{-1} & W; \\ \text{loading time } \tau_L &= \frac{E_L}{\bar{P}_L} = \frac{L}{f\ell_{sec}} \ln(1 - \frac{I_L \ell_{sec}}{2I_p M})^{-1} & s; \\ \text{stored energy } E_L &= \frac{1}{2} L I_L^2 & J; \end{aligned}$$

$$\text{lossed energy } E_{\text{loss}} = \left(\frac{4}{R} + \frac{1}{R_d} \right) \frac{f I_p M L}{2 \delta} \left(2 - \frac{I_L}{2 I_p} \cdot \frac{\lambda_{\text{sec}}}{M} \right) + \bar{P}_0 \tau_L \text{ J;}$$

$$\text{efficiency of energy conversion } \eta_E = 100 \left(1 + \frac{E_{\text{loss}}}{E_L} \right)^{-1} \%$$

in which:

- I_p = amplitude primary current at $t=0$22 A
- f = frequency primary current.....0.11 Hz
- δ = part of period used for pumping.....0.28
- M = mutual inductance = $k(\lambda_p \lambda_{\text{sec}})^{\frac{1}{2}}$1.70 mH
- λ_p = primary inductance transformer.....1.016 H
- λ_s = secondary inductance transformer.....3.68 μ H
- λ' = parasitical inductance in sec. of the tr....0.17 μ H
- λ_{sec} = secondary inductance = $\lambda_s + \lambda'$3.85 μ H
- k = couplings coefficient.....0.886
- L = inductance load coil.....112 μ H
- R = resistance open switch (S_1 or S_2).....2 $m\Omega$
- R_d = resistance dump resistor.....7.5 $m\Omega$
- \bar{P}_0 = mean power loss in heaters of switches.....65 mW.

The main components of the rectifier (see fig. 2) will be discussed consecutively.

Conductors and joints in the rectifier

Figure 3 shows the different conductors and joints in the rectifier. For the primary of the transformer a common 235 μ m MCA 367 fil. 7.4 μ m NbTi/Cu (I), is used. The secondary circuit is made of a home-made 144(4x4x3x3) strand cable (6 mm dia., 16.416 fil. 22 μ m) which is composed of a 350 μ m MCA 114 fil. 22 μ m NbTi/Cu30Ni wire (II). This cable is used for the secondary windings of the transformer as well as both rectifier switches and the protection switch. In this way the number of difficult joints is limited to the minimum: 4. Cable II is filled with PbSn solder except in the switches. According to the earlier tests with a 108 strand cable it could be expected that the 144 strand cable could carry the 10 kA at current changes less than 10 kA/s and maximal 8.6 kA at 25 kA/s. The load coil is made of a double monolytic NbTi/Cu conductor III as discussed below. The dump resistor (stainless steel strip V) is connected via two copper terminals IV parallel to the load coil. The joints between two 144 strand CuNi matrix cables are problematic. These soldered joints A_1 and A_2 are 25 cm long and each has a resistance of 1.25 n Ω at 9 kA. Both joints B_1 and B_2 between the Cu and CuNi matrix conductors are 40 cm long and each has a resistance of 0.75 n Ω at 9 kA. Consequently the decay time L/R_{joints} in the persistent mode (S_1 closed) is 21 hours in spite of the relatively small load inductance of 112 μ H.

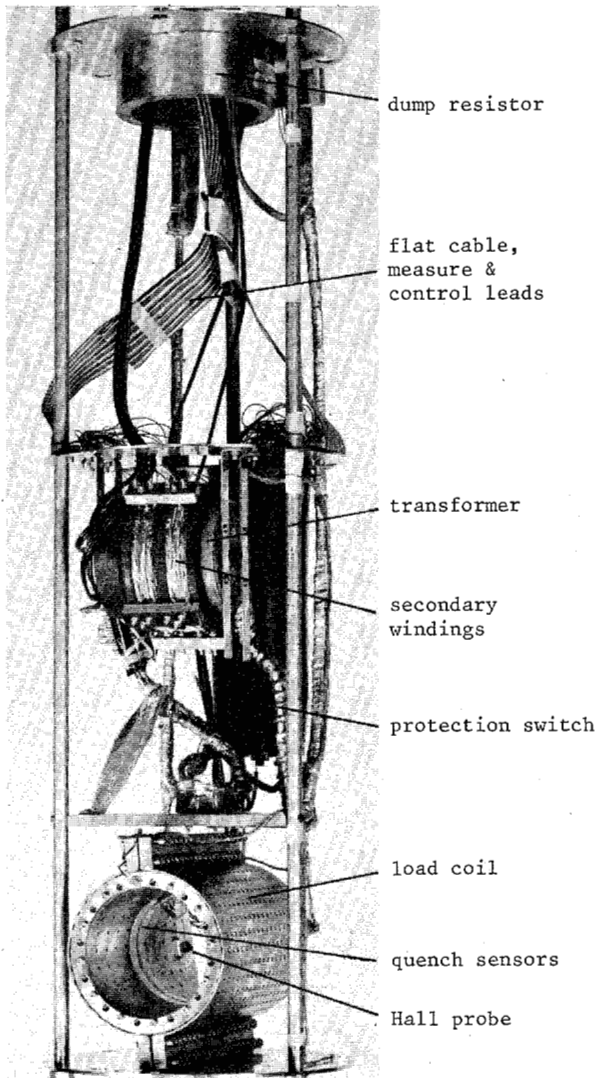


Fig. 2. View on the 9 kA rectifier.

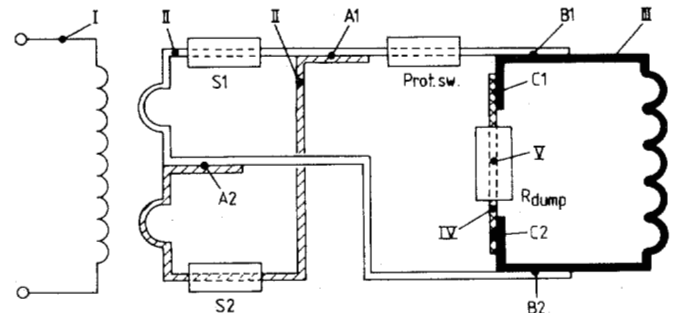


Fig. 3. Conductors and joints in the rectifier

Transformer. The primary inductance of the air-core transformer is determined from both the maximum current ($2 I_p M / \lambda_{\text{sec}}$) and the available primary power supply (I_p, I_p) to be 1 H. The special shape of the primary (fig. 4) is a compromise between a large coupling constant k and what can be realized in a simple way. The realized shape increases the transferred power $\propto k^2$ with 10% compared to a simple solenoid. The large coupling constant (0.886) implies at the same time that the 2x3 secondary windings lie in a low field i.e. in a low force region. The primary coil is vacuum impregnated with STYCAST 2850 FT to obtain a mechanical stable configuration. Thin copper wires, which lie in axial di-

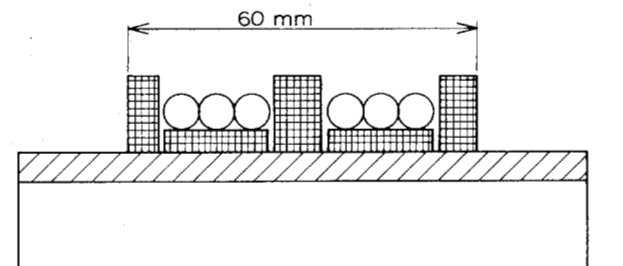


Fig. 4. Cross section of the transformer.

rection (low loss) and protrude into the helium, function as spacers between the layers and as a heat conductor at the same time. The central field in the transformer is 56 mT/A. A thermocouple senses the temperature in the transformer; its voltage serves as guard signal [4].

Two heaters allow forced quench studies of the transformer. The transformer operates trouble free.

Rectifier switches. Both thermally activated rectifier switches consist of the 144 strand cable, five heaters mounted in the centre and around the cable, a thermocouple and a tantalum sensor (fig. 5). In this way different heat power distributions can be tested and sufficient redundancy is present. The resistance barrier in the normal state (0.22 m Ω per cm) is determined by the length of the normal zone. This length is dependent on the total of heater power and V^2/R_{switch} dissipation due to the transformer voltage across R_{switch} . Figure 6 shows a detail of the load current, the primary current, the heat puls and the temperature in the switch in their mutual relation. The trigger heat puls of only 300 mJ is very small compared to other losses. It is clearly seen that the frequency to other primary current is limited by the recovery times of the switches. If this frequency is increased further the commutation starts before the temperature in the switch has recovered to nearly 4.2 K. This results in a lower maximum load current due to the temperature dependence of the critical current. This behaviour may be improved by reducing the thermal insulation of the switch or by increasing R.

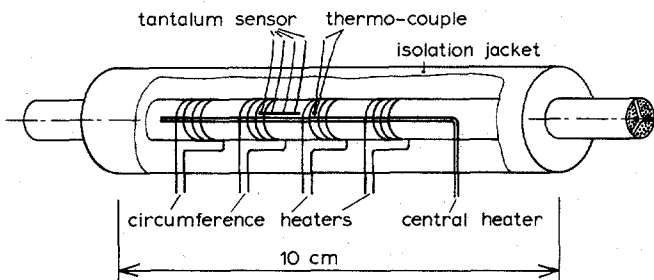


Fig. 5. Layout of rectifier switch.

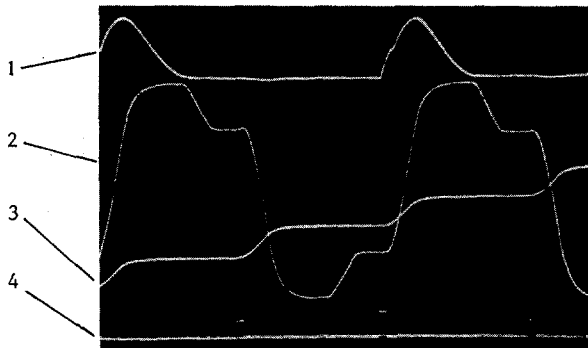


Fig. 6. Detail of load-curve: temperature in switch (1), (peak 18 K); primary current (2), (22 A amplitude); load current (3), (500 A per step); switch triggering pulses (4), (300 mJ).

Load coil. For the behaviour of the rectifier only the critical current, the inductance and the possible stray fields of the load coil are of interest. This load coil has been designed for 10 kA at 3 T and 112 μH . The coil has 43 windings in two layers on a stainless steel tube (12 cm dia., 17 cm long). The conductor consists of two parallel, side by side positioned, insulated with 100 μm thick glas fibre tape, IMI monoliths: 2(1.8x3.6 mm²), 4526 fil. 35 μm , twist 43.4 mm, Cu/sc = 1.77. All empty spaces between

the windings are filled up. The coil is wound with a pre-stress of 50 MPa. The radial stress $\sigma = \text{JBR}$ of about 140 MPa at 10 kA is compensated by a cylinder clamping the windings. In axial direction the windings are pressed between a fixed and a movable flange. The current density in the windings and the central field are 770 A/mm² at 10 kA and 0.259 T/kA respectively.

Protection. The rectifier has to be secured against the dissipation of the stored energy especially if one of the rectifier switches has been opened. Otherwise the secondary circuit of the rectifier will burn out in case of failure modes. Figure 7a shows the equivalent circuit of the rectifier with protection switch, dump resistor and load coil. During normal operation $R_{\text{prot.sw.}}$ and R_L are zero and $R_{\text{dump}} \gg R_{\text{rect,switch}}$. In case of a quench the protection switch is triggered and $R_{\text{prot.sw.}}$ has to be much greater than R_{dump} . $R_{\text{prot.sw.}}$ was determined by the total available length of the secondary conductor and is 125 m Ω . Figure 7b shows the energy distribution, the dump decay time and the dump voltage which are to be expected, in relation to the dump resistance after the protection switch has been opened. In the present case ($R_{\text{dump}} = 7.5 \text{ m}\Omega$) nearly 90% of the energy is dissipated in the dump resistor after the protection switch has been opened.

Protection switch. The protection switch consists of 5.7 m of the 144 strand cable which is bifilarly wound around on a 6 cm diameter glas fibre tube. Three independent heater systems can open the switch. The first one heats up the centre of the cable at 22 points distributed along the cable. The second one does the same at the circumference of the cable. A third one heats up the whole cable. Which one or which combination of heaters has to be preferred will be tested further. The cable is sufficiently isolated from the helium bath by a jacket of STYCAST 2850 FT. A thermocouple measures the temperature in the switch.

Dump resistor. The dump resistor (7.5 m Ω) is made of a bifilarly folded stainless steel strip with a mass of 0.08 kg. This packet is made mechanically stable by pouring it into Stycast 2850 KT. During a quench at 10 kA the resistor is exposed to internal stresses of 70 MPa and heats up about 100 degrees. The resistor is mounted in the cold gas above the helium bath.

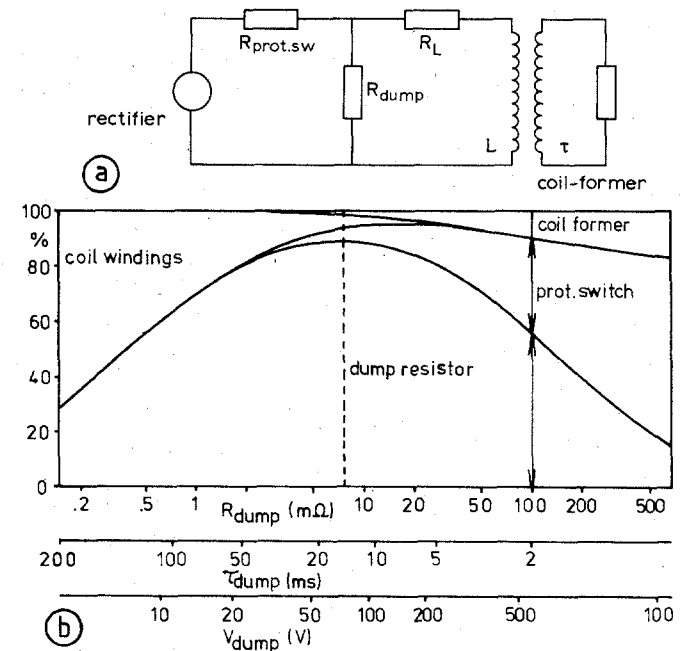


Fig. 7. Equivalent circuit of the rectifier in case of a quench (a) and the distribution of the energy dissipation (b).

Quench detection. The voltage of two equal pick up coils mounted inside the load coil and the voltage across the load itself are used as quench sensors. Quenches in the rectifier part of the circuit are seen by all sensors. A quench inside the load coil is mainly seen by the pick up coils. All sensors work independently so that each one triggers the protection switch separately. During normal operation the voltage across the load coil is the waveform shown in fig. 8. During the pumping period this voltage equals $\frac{1}{2}M I_p$ (typically 10-50mV). Because the commutation step can hardly be exactly a commutation peak occurs across the load coil if one of the rectifier switches opens. This peak is approximately equal to R_{dump} times the remaining current in the switch. In order to keep the detection level just above the permitted voltages the detector level is split into two levels as shown in fig. 8. Obviously the detector level reacts to both positive and negative signs of the voltages. The quench detector logic is made as simple as possible to obtain the best reliability. It contains a differential amplifier, a comparator, a timer (100 ms) and a transistor switch. The comparator level is controlled by the switch heater signals. Both detector logic and heaters of the protection switch are fed by batteries to be independent of line power failures.

Behaviour of protection system. The protection switch has operated well after both triggered and spontaneous quenches in the secondary circuit due to overcurrent. The delay time between a quench and the opening of the protection switch is about 4 ms. In that period about 10% of the energy is already dissipated at the hot spot (fig. 9) due to the relatively small load inductance. The temperature at the hot spot will not exceed 450 K. The current commutates into the dump resistor with 10 MA/s. The reaction time of the protection switch may be reduced by a different triggering.

Control system. The rectifier operates in combination with appropriate power supplies, which are controlled by a microcomputer [4]. The computersystem allows for dictation of max. load current, pump frequency etc. and directs the complete pump process including measurements, administration etc. Alternatively such a rectifier can be controlled by a simple hardware unit which only provides the input signals of the transformer and rectifier switches [5]. Of course a parallel hardware protection unit, described before, secures the rectifier system against fatalities.

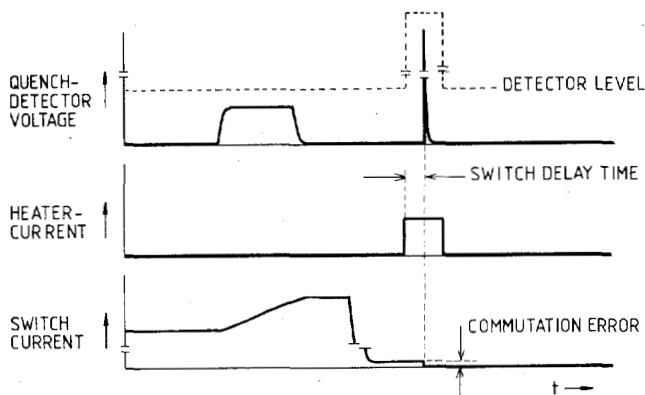


Fig. 8. Correlation between quench detector level and switch current.

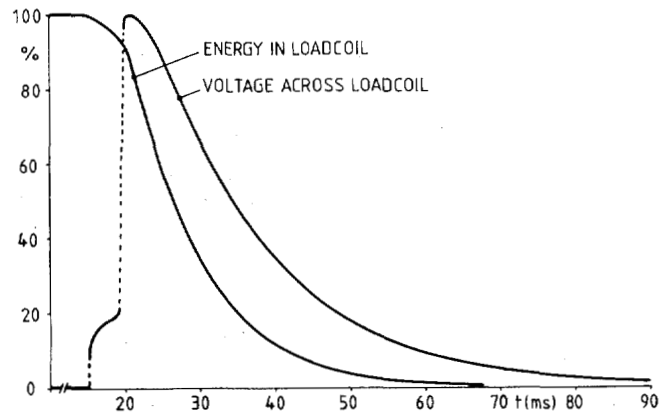


Fig. 9. Energy content and voltage across the load coil after a triggered quench at 7.6 kA.

CONCLUSION

The superconducting rectifier presented above is assembled in February 1981 and is still under test. Yet, the rectifier has proven to operate reliable at current levels up to 9 kA. As an example it charged the 112 μ H load coil to an energy level of 4500 J at 9 kA with a mean power of 30 W, loading time 150 seconds, efficiency of the energy conversion 99.1%. Transformer, rectifier switches, protection system and load coil perform their task trouble free. The secondary 144 strand cable quenches consequently and repeatable at 9 kA. The load coil designed for 10 kA has never quenched spontaneously until now. Next month's further tests will concern the multi strand cable and the current sharing in the joints in order to improve the already achieved load current. After that the next goal will be a thermally switched 25 kA rectifier. Also the operation of thermally switched rectifiers in a background-field of 4-5 tesla's is studied.

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REFERENCES

- [1] L.J.M. van de Klundert and H.H.J. ten Kate, "On fully superconducting rectifiers and fluxpumps". A review. Part I: "Realized methods for pumping flux," in *Cryogenics*, 21, 1981, pp. 195-206. Part II: "Commutation modes, characteristics and switches," in *Cryogenics*, 21, 1981, pp. 267-277.
- [2] H.H.J. ten Kate, P.B. Bunk, R.B. Britton and L.J.M. van de Klundert, "High current and high power superconducting rectifiers," in *Cryogenics*, 21, 1981, pp. 291-296.
- [3] D.E. Spiel and R.W. Boom, "Superconductive energy storage with a flux pump," Int. Inst. of Refrigeration Low Temp. and Electric Power, Conf. London, 1969, (Pergamon Press, NY 1970), pp. 438.
- [4] H.H.J. ten Kate, D.A. Kamphuis, M. Caspari, L.J.M. van de Klundert and Z. Houkes, "IEEE MAG. 18," MT 7 Conference Karlsruhe, March 30, 1981.
- [5] P.B. Bunk, M. Caspari, H.H.J. ten Kate and L.J.M. van de Klundert, "Hardware control unit for superconducting rectifiers," to be published.