THERMALLY AND MAGNETICALLY CONTROLLED SUPERCONDUCTING RECTIFIERS

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Abstract

The switches of a superconducting rectifier can be controlled either magnetically or thermally. The main purpose of this paper is to point out the differences between both methods of switching and discuss the consequences for the operation of the rectifier. The discussion is illustrated by the experimental results of a rectifier which was tested with magnetically as well as thermally controlled switches. It has an input current of 30 A, an output current of more than 1 kA and an operating frequency of a few Hertz. A superconducting magnet connected to this rectifier can be energized at a rate exceeding 1 MJ/hour and an efficiency of about 97 %.

Introduction

Superconducting rectifiers can be used as current supplies for high-current superconducting coils. Thus, high-current input leads become superfluous and the heat leak to the cryostat is almost eliminated. Basically, a rectifier converts an a.c. input current to a d.c. current level that is suitable for the coil.

The possibility of energizing superconducting coils by means of superconducting rectifiers has been a subject of research at the University of Twente since 1979. At first, the investigations were focussed on thermally controlled rectifiers operating at a relatively low frequency of about 0.1 Hz. During this period several experimental rectifiers were developed, including a 9 kA, 50 W and a 25 kA, 500 W model.[1] The main disadvantage of low-frequency operation is that the transformer has to be rather large in order to achieve high output power. In fact, the average power of the rectifier is proportional to the product of operating frequency and primary energy of the transformer. Therefore, in the past four years we have concentrated on raising the frequency by improving the speed of the superconducting rectifier switches.[2,3,4]

Principle

A particular type of rectifier that was used in the experiments is the full-wave rectifier with inductive commutation of the secondary current. Its principle is explained by means of the diagrams in figure 1. The alternating primary current I_P is converted into a step-wise changing current I_L through the load. The load current either increases or decreases depending on the sequence of the control signals. The diagrams, which correspond to an increasing I_L, show that each half-cycle of operation is made up of four stages:

1) pumping stage, where a step in the primary current effects an increase of the load current.
2) recovery stage, where the primary current remains constant to allow one of the switches to be closed.
3) commutation stage, where a step in the primary current, while both switches are closed, causes the current in one half of the secondary circuit to be transferred to the other half.
4) trigger stage, where the primary current is kept constant so that the appropriate switch can be opened.

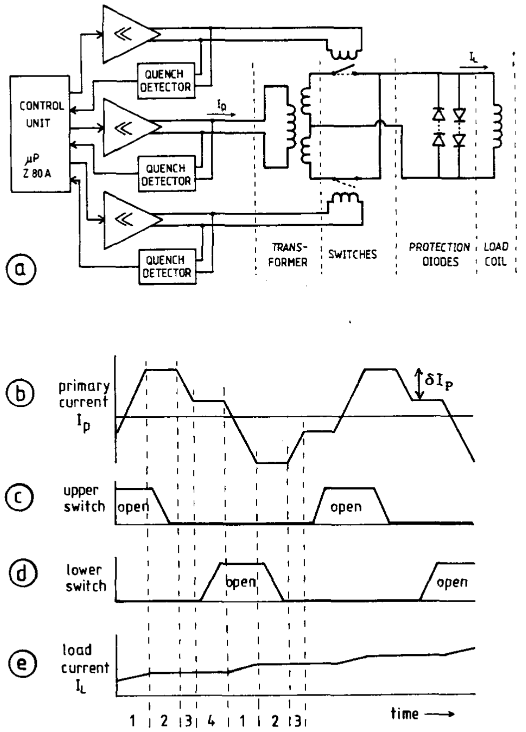

Fig. 1. A full-wave superconducting rectifier shown here with magnetically controlled switches,
a) scheme of the rectifier system,
b) primary current of the transformer,
c) status of the upper switch,
d) status of the lower switch,
e) step-wise increasing load current.

The actual increase of I_L takes place during the pumping intervals. During the commutation intervals I_L remains constant, but the current present in one of the switches is transferred to the other switch by making an appropriate step in the primary current. The purpose of this so-called inductive commutation is to nullify the current in the switch that has to be opened in the next fase of the rectifying process. In this way the efficiency is improved, since ohmic dissipation in the switches during the trigger stage is avoided. The magnitude of the commutation step, indicated as δI_P in figure 1, is proportional to the current in the secondary circuit. Therefore, the momentary value of the load current I_L has to be measured and fed back into the control unit in order to obtain correct rectifier operation.

In well-designed rectifiers, the self-inductance of the switches and their wiring is usually negligibly small compared to the self-inductance of the secondary transformer coils. In this case, the maximum output current I_{MAX} that can be produced by the rectifier is given by

$$I_{MAX} = 2\,\hat{I}_P\,k\,\sqrt{L_P / L_S}\ . \qquad (1)$$

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Consider the process of energizing a load coil from zero up to a certain value I_L. Then, provided f is constant, the load current tends exponentially towards I_{MAX},

$$I_L(t) = I_{MAX} \left[1- \exp\{- \frac{f\, L_S}{L_L} t\} \right] , \qquad (2)$$

and the average power delivered to the load can be expressed as

$$\bar{P}_L = \alpha\, f\, k^2 \tfrac{1}{2} L_P \hat{I}_P{}^2 , \qquad (3)$$

with

$$\alpha = 4\, (I_L/I_{MAX})^2 / \ln\left(\frac{1}{1-I_L/I_{MAX}}\right) . \qquad (4)$$

The factor α has a maximum of 1.63 when the current I_L in the load is 71.5 % of I_{MAX}. It should be noted that the operating frequency is not necessarily constant. In order to improve the performance of the rectifier it is in fact preferable to let the time intervals used for pumping and commutation depend on I_L. As a result, the frequency will change during the operation of the rectifier. A control unit which generates such a variable frequency was actually applied during our latest experiments, see table 1 configuration 3.

Thermally and magnetically controlled switches

The rectifier switches consist of a switch element, so-called gate, which is either in the superconducting or in the normal state. The gate is usually a superconducting cable having a high-resistivity matrix and wound in a low-inductive manner. Control of the gate, i.e. turning it on and off, is achieved magnetically or thermally. Magnetic control is obtained by placing the gate in a superconducting coil capable of generating fields exceeding the critical field of the gate material. Thermal control, on the other hand, is obtained by means of a heating element which can heat up the gate to above its critical temperature.

Magnetic switching is the faster method, provided a sufficiently fast control field can be generated. In practice, generating fast control fields may be a problem in view of the rather large self-inductance of the control coil. Hence, it depends entirely on the power supply for the coil whether magnetic switching is really faster than thermal switching.

Description of the rectifier system

Figure 2 shows the lay-out of the cryogenic part of the experimental rectifier system mounted in a 0.27 m diameter cryostat. Undesired mechanical or magnetic interaction between the rectifier components was avoided by properly positioning them in the cryostat. The solenoidal transformer, for example, was placed horizontally in the cryostat with its axis perpendicular to that of the load coil in order to prevent magnetic coupling. The various components are electrically connected by joints produced as follows. After removing the electrical insulation of the conductors, they are pressed together side by side and soldered with Sn3%Ag onto a 1 cm wide copper strip over a length of about 20 cm. The measured time constant of the secondary circuit is 3 weeks, which indicates a resistance of less than 3 nΩ for the 1 kA joints.

The transformer. Two "air-core" transformers were constructed and tested while operating in the rectifier circuit. The electrical specifications of both transformers are almost identical (see table 1), but one has a toroidal shape and the other a solenoidal shape. For the primary windings, a multifilamentary NbTi conductor is applied (0.3 mm diameter, Cu30%Ni-matrix and 574 filaments of 8.6 µm). The same wire is used for the secondary windings after twisting it into a 24-strands cable.

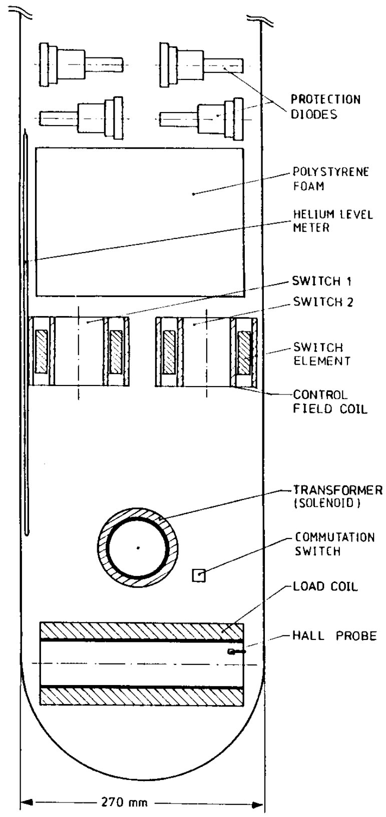

Fig. 2. Trenched view of the rectifier, shown here with magnetically controlled switches and a solenoidal transformer.

The main advantage of the toroid is the absence of a stray field so that there is no interaction between the transformer and the other components of the rectifier. The disadvantages are numerous: the toroid is more expensive and complicated to produce, requires 2 to 3 times more conductor, occupies more cryogenic volume and has an inferior cooling of the windings. In the experiments, the type of transformer appears to have no influence on the operating characteristics of the rectifier. Hence, a solenoidal shape is preferable unless a very low stray field is a pre-requisite.

Magnetically controlled switches. The conductor used in the gates is a Nb1%Zr multifilamentary conductor with a critical field of about 0.8 T (0.3 mm diam., Cu30%Ni-matrix and 574 filaments of 8.6 µm). This conductor is cabled into a 24-strands cable having a low self-inductance, low self-field and a homogeneous distribution of the current over the 24 parallel strands.[2,3] The open-state resistance of the gate is 0.88 Ω and 0.69 Ω for switches 1 and 2 respectively.

The control coils are wound from the same 574-filaments conductor as the transformer. Each control coil consists of an inner and outer solenoid connected in anti-series, see figure 2. The purpose of this lay-out is to achieve an good field homogeneity at the switch element and simultaneously minimize the self-inductance of the control coil. The resulting inductance of the control coils is 0.16 H for switch 1 and 0.21 H for switch 2.

Thermally controlled switches. The development of these switches has been described previously.[4] The conductor in the thermally controlled switches is a 144-strands braided flat cable. The single strand is a 74 μm thick NbTi monofilament without matrix. A heater wire is inserted inside the braid. The combination of braid and heater is thermally insulated from the helium bath by means of two 130 μm thick Kapton foils applied on both sides of the flat cable. The switches have a off-resistance of 0.84 Ω and can be triggered within 10 ms using a heater energy of about 0.25 J. Their recovery time is approximately 40 ms.

The load coil. The load coil is a solenoid having a length of 23 cm, an inner bore of 5.7 cm and a self-inductance of 13.5 mH. Its maximum current is 1200 A corresponding to a central field of 5.4 T and a stored energy of 9.7 kJ. Such a relatively small energy is desirable in order to keep the helium consumption during the experiments within acceptable limits. A Hall probe located within the load coil measures the secondary current and provides the necessary feed-back to the control unit.

Quench protection. The secondary part of the rectifier system is protected against quenches by means of protection diodes connected across the load coil as indicated in figure 1. Such a passive protection scheme is applicable here because the stored energy in the load coil is rather small, only 9 kJ at full current. The primary part of the rectifier is actively protected by means of a quench detector which monitors the resistive voltage across the primary coil of the transformer. Whenever a quench is sensed, the current through the transformer is shut off within a few milliseconds. A similar protection method is used for the control coils of the magnetically controlled switches. Note that the applied conductors in the rectifier have either a high-resistive CuNi-matrix or no matrix at all. As a result, to avoid a burn-out of the conductor, the duration of a quench should not exceed about 10 ms.

Experimental results and discussion

Table 1 gives an overview of the configurations in which the experimental rectifier was consecutively tested. Also, the table summarizes the main results concerning the performance, i.e. the maximum achieved load current, the frequency, the average load power and the efficiency.

Load current. In the first tests, the achievable load current was limited by the primary power amplifier. The AMCRON M-600 amplifier in practice delivers an amplitude of about 20 A, which corresponds to a maximum load current of 1 kA according to equation 1. Later on, in configuration 3, the M-600 was replaced by a more powerful home-built amplifier and a primary amplitude of up to 40 A could be generated. Now, the theoretical value of I_{MAX} is 2 kA. The maximum value of I_L that could actually be achieved, however, was limited by the critical current of the load coil to about 1.2 kA. Figure 3 shows a typical example of I_L as a function of time corresponding to the thermally controlled rectifier. The load current, which is pumped up and down between 0 and 1 kA, agrees within 2 % with the theory.

Table 1. Summary of rectifier tests.

configuration	1	2	3
date of the experiments	August and September '86	June '87	November and December '87
type of rectifier switches	magnetically controlled 0.88 & 0.69 Ω	thermally controlled 0.84 Ω each	thermally controlled 0.84 Ω each
transformer	toroid L_P= 193 mH L_S= 265 μH k = 0.973	solenoid L_P= 184 mH L_S= 232 μH k = 0.975	solenoid L_P= 184 mH L_S= 232 μH k = 0.975
load coil	L_L= 13.5 mH K = 4.48 mT/A	L_L=13.5 mH K =4.48 mT/A	L_L=13.5 mH K =4.48 mT/A
primary power amplifier	AMCRON M-600 50 V/ 25 A	AMCRON M-600 50 V/ 25 A	home-built 200 V/ 40 A
maximum load current	1.0 kA	0.97 kA	1.16 kA
operating frequency	1.2 Hz constant	2.3 Hz constant	1 to 4 Hz variable
best obtained average power	60 W	140 W	320 W
best obtained efficiency	94 % (calculated)	96 % (measured)	97 % (measured)

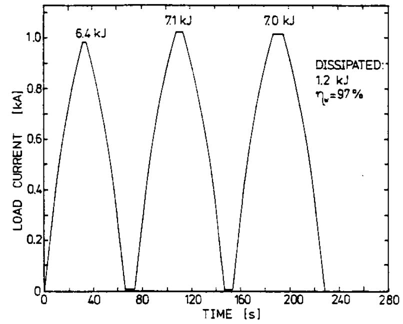

Fig. 3. Load curve corresponding to configuration 3 and $\hat{I}_P$= 30 A.

Power and frequency. As mentioned previously, the power depends closely on the operating parameters such as f, $\hat{I}_P$ and the current I_L which is in the load. Depending on the type of control signals, optimum average power is found when I_L is 60 to 80 % of I_{MAX}. In principle, the magnetically controlled rectifier should be able to deliver well over 500 W, however, the electrical equipment at room temperature prevents the rectifier from being used at full power. Firstly, the primary amplitude is too small, only 20 A instead of the design value of 30 A. Secondly, the control amplifiers limit the trigger and recovery times of the switches from 50 to 100 ms.

In the thermally switched rectifier (configuration 3) the power is really limited by the switches and not by the control equipment. Triggering of the switches requires 10 ms and recovery 40 ms. The length of the pumping and commutation intervals is also fixed by the switches because they will quench if $d\hat{I}_P/dt$ exceeds 400 A/s during the pumping stage or 1000 A/s during the commutation stage. The maximum obtained frequency was about 4 Hz and the average power 320 W.

Efficiency. Concerning the overall efficiency, a distinction has to be made between magnetic or thermal control of the rectifier. In the magnetically switched rectifier, all relevant loss contributions are proportional to f except for the ohmic dissipation in the switches during the pumping interval which is proportional to f^2. Therefore, the efficiency is not only a function of $\hat{I}_P$ and I_L, but also of f. Figure 4 shows this frequency dependence in the case $\hat{I}_P$=30 A.

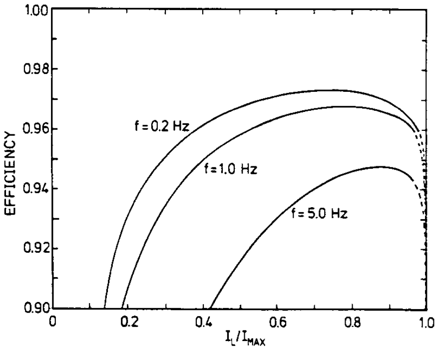

Fig. 4. Calculated efficiency of the magnetically controlled rectifier (configuration 1) as a function of f and I_L for $\hat{I}_P$= 30 A.

On the contrary, in the thermally switched rectifier, the dissipation in the rectifier switches during the pumping interval is proportional to f and not to f^2. As a result, the efficiency is independent of f and only a function of $\hat{I}_P$ and I_L. Figure 5 shows the calculated and measured results for the thermally controlled rectifier. The measurements are performed calorimetrically by registering the helium level while pumping up and down several times. The best efficiency is obtained for a large primary amplitude and amounts to 97 %.

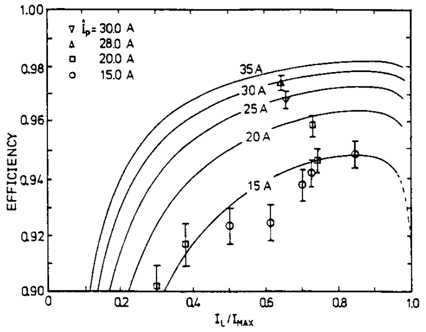

Fig. 5. Calculated and measured efficiency of the thermally switched rectifier (configuration 3) as a function of I_L and $\hat{I}_P$.

Quench behaviour. During the experiments, it was established that the rectifier is completely safe against faulty operating conditions. Three types of quenches were encountered.

1) When pumping up, the load coil will quench if its maximum current of 1.2 kA is exceeded. Then, the stored energy is completely dissipated inside the load coil itself and the rectifier remains superconducting.
2) A quench in the rectifier switches occurs when both switches are simultaneously open, for example due to a too low helium level.
3) A quench in the secondary part of the transformer can occur due to faulty control signals which cause a too large commutation error.

In the latter two cases, about 2 % of the stored energy is dissipated in the rectifier and the rest in the protection diodes. The load coil remains superconducting.

Conclusions

A fast operating rectifier system was developed and tested in several configurations. The best results were obtained using thermally controlled switches. With a power of over 300 W this is one of the most powerful superconduting rectifiers ever built. The efficiency is 97 %. The rectifier was used in combination with a 1.2 kA, 9 kJ magnet, which could be charged in 30 s and with a helium consumption of only 100 ml.

A comparison of solenoidal and toroidal transformers shows a preference for the solenoidal shape. Concerning the switches there is a preference for the thermally controlled type on practical grounds. In theory larger power can be obtained with magnetically controlled switches, however they are unpractical for several reasons, such as :

- * The required amount of conductor is about 50 times as large due to the low resistivity of Nb1%Zr and the presence of control coils. As a result, they are accordingly expensive.
- * The achievable frequency is dissapointing unless relatively high control power is used.
- * The production is more complicated.

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List of symbols

f	operating frequency of the rectifier
$I_P, \hat{I}_P$	primary current, and its amplitude
I_L, I_{MAX}	load current, and its theoretical maximum
k	coupling constant of the transformer
L_P, L_S, L_L	self-inductances of the primary coil, both secondary coils, and the load coil
$\bar{P}_L$	average load power, $\bar{P}_L = W_L/T_L$
T_L	time to energize the load from zero to I_L
W_L	stored energy in the load, i.e. $\frac{1}{2}L_L I_L^2$
W_{LOSS}	energy dissipated in the cryostat during T_L
η_W	overall efficiency, $\eta_W = W_L/(W_L+W_{LOSS})$

References

[1] H.H.J. ten Kate, Superconducting Rectifiers, Thesis University of Twente, Enschede, 1984.

[2] G.B.J. Mulder, Increasing the operating frequency of superconducting rectifiers, Thesis University of Twente, Enschede, 1988.

[3] G.B.J. Mulder, H.J.G. Krooshoop, A. Nijhuis, H.H.J. ten Kate and L.J.M. van de Klundert, "A high-power magnetically switched superconducting rectifier operating at 5 Hz", IEEE Transactions on Magnetics, vol. MAG-23, pp. 595, 1987.

[4] G.B.J. Mulder, D. ter Avest, H.H.J. ten Kate, H.J.G. Krooshoop and L.J.M. van de Klundert, "Experimental results of thermally controlled superconducting switches for high frequency operation", IEEE Transactions Magnetics, Vol. MAG-24, pp. 907, 1988.

[5] G.B.J. Mulder, H.H.J.ten Kate, H.J.G. Krooshoop and L.J.M. van de Klundert, "Efficiency aspects in superconducting rectifiers", Advances in Cryogenic Engineering, vol. 30, pp. 117, 1988.