A FAST OPERATING MAGNETICALLY CONTROLLED SWITCH FOR 1 kA

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Abstract

The power of fully superconducting rectifiers can be improved by increasing either the operating frequency or the transformer primary inductance [1]. The frequency is usually limited by the recovery time of thermally controlled switches. In order to achieve a higher switching speed, magnetically controlled switches are preferable [1,2]. This paper describes a magnetically controlled switch which can be used for currents up to 500 A at 25 Hz. The switch element, consisting of several Nb1%Zr multifilamentary superconductors, is placed between two concentric solenoids which generate the necessary magnetic field. The Nb1%Zr superconductor is well suited for this purpose because of its relatively low critical field (≈ 0.75 T) and high maximum current density (about $5 \cdot 10^9$ A/m² below 0.3 T).

Introduction

Necessary components of fully superconducting rectifiers are at least two superconducting switches which can be controlled externally, i.e. outside the cryostat. The maximum operating frequency of a sc. rectifier is in practice always limited by the applied switches. Since increasing the frequency is one means of increasing the mean power of a rectifier, it is advantageous to design a sc. switch with very short switching-on and switching-off times.

All sc. switches have in common that they consist of a switch element or gate that can be either in the superconducting state (switch is closed) or in the normal state (switch is open). The classification of sc. switches depends on the mechanism used to effectuate the superconductive to normal transition of the gate. Two important types are: thermally controlled switches in which the gate is heated above its critical temperature T_c and magnetically controlled switches in which an overcritical field is applied to the gate. Theoretical considerations [3] and experiments [2] show that the highest switching speed can be obtained with a magnetically controlled switch, but that this type of switch has important drawbacks: The required switch volume is relatively large which leads to the challenging problem of realizing high field changes in a large volume. In the past 5 years, several fully superconducting rectifiers were built and successfully tested at the Twente University of Technology. In most of them the frequency was limited to below 0.1 Hz while thermally switched. In order to investigate the performance of sc. rectifiers at substantially higher frequencies, say 1 to 10 Hz, we developed a magnetic switch described in this paper.

General aspects of magnetically controlled switches

Figure 1 gives a schematic representation of a sc. magnetically controlled switch. The field coil in combination with a control unit and a power amplifier provides a magnetic field B at the gate. The operation of the switch is indicated in figure 2. B is cycled between a low value B_{min} at which the gate is able to carry its design current and a high value B_{max} at which the gate has the desired 'off-resistance'. The figure is applicable for a sc. rectifier in the inductive commutation mode because switching on and off occurs precisely when the gate current is (passing through) zero. There is no abrupt change in R_{sw} when B is raised just above B_{c2} (fig. 2b). The reason is that the gate can be partly normal if the field at the switch element is inhomogeneous or if the switch conductor itself is inhomogeneous, i.e. B_c varies along the conductor. A hysteresis effect in curve $R_{sw}(B)$ of figure 2 is seen. R_{sw} is not only a function of B (this would be perfect magnetic switching) but also depends on the direction of B , the leakage current I_{sw} , the temperature of the gate, etc...

Figure 1. Schematic circuit of the magnetic switch : 1--control unit; 2--power amplifier; 3--gate terminals; L_{sw} --self-inductance of the gate; R_{sw} --gate resistance; L_f --self-inductance of the control field coil.

The feasibility of a magnetically controlled switch is largely determined by the switching losses, which must therefore be minimized. In the first place, dissipation in the gate could raise its temperature during the off-state. This temperature increase must be minimal otherwise the switch recovery time will depend on thermal diffusion resulting in a combination of thermal and magnetic switching. It is evident that thorough cooling of the gate is indispensable. In the second place, the overall losses (including those in the control field coil) must be small if the switch is to be used in a high efficiency sc. rectifier. (A rule of thumb is that the average dissipation in a switch must be less than 1 % of the rectifier power).

A distinction can be made between three sources of dissipation.

- 1 Loss in the field coil when cycled between B_{min} and B_{max} : in case of a CuNi matrix conductor, mainly due to magnetization of the sc. filaments in the coil windings.
- 2 Loss in the switch element during the on-state: mainly due to magnetization of the superconductor in the gate.
- 3 Loss in the switch element during the off-state: this ohmic loss is caused by a voltage across the switch terminals during the off-state.

Loss contribution 3 is for a given application inversely proportional to R_{sw} . Reduction of this loss contribution therefore implies an increased switch volume V_{sw} . On the other hand, loss contributions 1 and 2 are proportional to V_{sw} . Obviously, there is an optimum in V_{sw} depending on the particular operating conditions such as: frequency, gate current, gate voltage during off-state, B_{min} , and B_{max} .

Conductor choice

According to the previous section, the switch must have a large off-resistance, small switch volume and low critical field. To what extent we can satisfy these conflicting requirements primarily depends on the sc. material in the gate. Subsequently we shall restrict ourselves to type II superconductors because we are of the opinion they are preferable for magnetic switching. Physical parameters characterizing the gate material are the resistivity of the superconductor in the normal state ρ_{sc} , the critical current density J_c , and the second critical field B_{c2} .

The cross-sectional area of the switch conductor necessary to carry the design current I_{max} is

$$A_c = s \cdot I_{max} / (\eta J_c) \quad (1)$$

Here s is a safety factor included to ensure a reliable operation and η is the filling factor of sc. material in a composite wire. For massive superconductors η can be taken 1. If a composite wire is used, the matrix must have a high resistivity ρ_m in order not to reduce R_{sw} . The average longitudinal resistivity of the composite is given by

$$\bar{\rho} = (\rho_{sc} \rho_m) / (\eta \rho_m + (1-\eta) \rho_{sc}) \quad (2)$$

$$= \rho_{sc} / \eta \text{ if } \rho_m \gg \rho_{sc} \quad (3)$$

The conductor length is determined by the desired off-resistance

$$l = R_{sw} \cdot A_c / \bar{\rho} \quad (4)$$

The conductor cannot occupy the entire switch volume because materials for cooling, electrical insulation, and mechanical stabilization must also be present. We assume a filling factor ϕ for the conductor (so $V_c = \phi \cdot V_{sw}$) and calculate V_{sw} from (1) and (4)

$$V_{sw} = \frac{s^2}{\phi \eta^2} \cdot \frac{R_{sw} I_{max}^2}{\bar{\rho} J_c^2} \quad (5)$$

The importance of a high energy density $\rho_{sc} J_c^2$ and a high filling factor $\phi \eta^2$ can now be seen. Unfortunately, sc. materials with high energy densities have high critical fields. It is experimentally observed that large values of J_c and B_{c2} usually go together. Furthermore we can conclude from the Gorkov-Goodman relation that for type II materials, $B_{c2} = c_1 + c_2 \cdot \rho_{sc}$, where c_1 and c_2 are constants. Therefore, a large value of ρ_{sc} implies a high second critical field. It is difficult to realize sc. coils which can produce large a.c. fields. In the frequency range of 5 to 50 Hz, 1 Tesla is sometimes mentioned as a practical limit; hence, the value of J_c is also limited. In reference [3], an optimum value of ρ_{sc} between 1 and $2 \mu\Omega \text{ cm}$ is calculated. Our choice of Nb1%Zr with $\rho_{sc} = 1.8 \mu\Omega \text{ cm}$ is close to this optimum.

Another important consideration is the loss in the conductors of both the gate and the control field coil because they are subject to large field changes. The dimensions of the sc. material perpendicular to the field must be small in order to reduce magnetization losses (for instance filaments, foil, thin films). Eddy current loss in the matrix can be reduced by using highly resistive matrix material (for instance CuNi).

Data about the conductors used for the gate and the field coil are given in table 1. Improvement is still possible here by scaling down the filament sizes. Recent publications about 50 Hz multifilamentary wires with very thin filaments ($\approx 1 \mu\text{m}$) and low a.c. losses are optimistic. The commercial availability of these wires however, is still very poor and the situation is even worse for multifilamentary wires with a low critical field.

Figure 2. Theoretic operation diagrams of a magnetically controlled switch.

Not only the switch volume has to be considered, but also the geometry of the switch element. The importance of a bifilar arrangement is illustrated by the following advantages:

- A changing field at the switch element does not induce a gate current because it has no magnetic coupling with the environment.
- The net Lorentz force on the switch element is zero.
- The self-inductance of the gate is small which means that energy storage in the gate is avoided.
- The self-magnetic field caused by the gate current is small and degradation of the maximum switching current by this self-field is therefore minimized.

Table 1. Conductor specifications

	conductor in switch element	conductor in field coil
manufacturer	Supercon	MCA
material	Nb1%Zr/Cu30%Ni	NbTi/CuNi
N filaments	18	574
Ø wire [µm]	310	300
Ø filament [µm]	48	8.6
matrix : sc. ratio	1.2	1.1
$\rho_{sc} \times 10^{-8}$ [Ω m]	1.8	-
$\bar{\rho} \times 10^{-8}$ [Ω m]	3.5	-
Bc ₂ at 4.2 K [T]	0.75	10.5
Jc * 10 ⁹ [A/m ²]	5	7
(for B below 0.3 T)		

Construction of the switch

The switch element

The Nb1%Zr multifilamentary wire (given in table 1) has a critical field of about 0.75 T. If these wires are cabled to improve the current carrying capacity, it is found that the maximum current is not proportional to the number of strands. Because Bc₂ is relatively low, the self-magnetic field due to the gate current can cause a serious decrease of Jc. In order to avoid this effect, the switch conductor was produced according to a new technique: Subcables of 4 strands were bifilarly twisted as indicated in figure 3. Adjacent strands always carry opposite currents so the self-magnetic field is minimized. Six subcables were again twisted around a central nichrome core to form a 9 meter long cable. This non-inductive cable is wound in two layers on the inner field coil and impregnated with STYCAST 2850 FT epoxy. Thin copper heat-drains and cooling channels between the two layers allow the dissipated heat to be conducted away in axial direction.

Computer calculations show a maximum self-field of 200 mT at I_{sw}=1 kA for this cable geometry. In these calculations, equal currents in the different strands are assumed. In practice however, the current is usually non-uniformly distributed over the strands. The measured off-resistance of the gate is 0.6 Ω at 4.2 K and the self-inductance is approximately 0.2 µH. The field at the switch element is homogeneous within 5 %. If we define the switch volume V_{sw} as the volume between the inner and outer coils, then the filling factor ϕ is only 0.11. It should be noted here that V_{sw} is large enough to contain a switch conductor length of 20 metres, giving $\phi \approx 0.25$ and R_{sw}=1.3 Ω.

Figure 3a. Cross-sectional view of the switch.

Control field coil

The field coil consists of an inner and outer solenoid with opposite current directions. The available switch volume V_{sw} between the two solenoids is 0.145 litres. In this geometry, 60 % of the field energy is concentrated in V_{sw}. Furthermore, a reasonable field homogeneity in V_{sw} is obtained being 90 % of the maximum field at 1 cm from the coil edges. Both solenoids were wound with NbTi/CuNi multifilamentary wire.

The use of a CuNi matrix imposes extra demands on the coil manufacture:

- 1) CuNi and epoxy have a bad thermal conductivity so heat-drains are required to conduct dissipated heat from the coil interior to the helium bath. This was achieved by thin copper wires (0.25 mm dia) which lie in axial direction between the winding layers, with a mutual distance of 0.4 mm.
- 2) Wires having a CuNi matrix are extremely sensitive to mechanical disturbances. Therefore both solenoids were impregnated with STYCAST 2850 FT filled epoxy. The inner coil was vacuum impregnated and the outer coil was wet-wound.

In order to estimate the necessary amount of heat-drains, the loss in the field coil was calculated according to the method given in reference [4]. This yields 0.50 Joule/period for cycling between B_{min}=0 and B_{max}=0.75 T. In the range of interest, this loss per period is proportional to (B_{max}-B_{min}).

Table 2. Field coil data

Inner coil:	7 layers, 2009 turns, inner radius 25 mm, outer radius 30 mm, self inductance 84 mH.
Outer coil:	7 layers, 1940 turns, inner radius 37 mm, outer radius 42 mm, self-inductance 156 mH.
combination:	wire length 845 m, self-inductance 80 mH, magnetic field 23 mT/A, V _{sw} 0.145 litres.

Figure 3b. Gate conductor cross-section.

Experimental results and discussion

The inner and outer solenoids were separately tested with sinusoidal currents. The outer coil could stably generate field amplitudes above 0.5 T at 50 Hz and the available power was insufficient to quench it. The inner coil quenched at 0.4 T, 50 Hz. Also at other frequencies, the outer coil definitely showed better results than the inner coil. The reason for this is that the central parts of the inner solenoid are not filled with epoxy as a result of an imperfect vacuum impregnation process. In this a.c. coil, the windings and heat-drains are so closely packed, that a good internal impregnation with filled epoxy is only possible by wet-winding as was done for the outer coil. The measurements demonstrate the importance of a good mechanical fixation of the windings. The combination inner/outer solenoid can generate the desired field sweep between 0 and 0.75 T at frequencies of at least 25 Hz.

Measurements of the current carrying capacity of the switch element in a d.c. magnetic field are given in figure 4. A sinusoidal gate current is induced by means of a sc. transformer (primary inductance 0.26 H, secondary inductance 0.5 μ H) which is connected to the gate terminals. The voltage of a toroidal Rogowsky coil around the switch conductor is integrated to give the gate current.

Figure 6 shows measurements of the maximum current that can be actually switched, as a function of the frequency. The measurements were carried out for $B_{min} = 0$, $B_{max} = B_{c2}$, and $\tau_1 = \tau_2 = 30$ ms. If the transformer primary current is sinusoidal, then the gate current will be a rectified sine wave as indicated in figure 2. The presence of an a.c. field decreases the maximum gate current from 1100 A to about 600 A. It is not likely that this decrease is caused by losses in the gate because we see roughly the same degradation for all frequencies between 0.5 and 25 Hz. We assume that the a.c. field induces undesirable circulation currents in the switch element which have a detrimental influence on the maximum gate current. This assumption is confirmed by the following experiment. After one fieldsweep to B_{c2} and back to zero, the maximum current amplitude is measured. We find only 600 A and it takes several quenches of the gate before 1100 A is reached again.

Concluding remarks

We have developed a production technique for a.c. coils which looks promising. Field amplitudes above 0.5 T at 50 Hz can be generated with such coils, and a great deal of improvement is possible by reducing the hysteresis loss.

The bifilar switch element can carry its design current of 1 kA at frequencies up to 25 Hz and d.c. fields up to 0.2 T. During the actual switching operation, an a.c. field is applied to the switch element which gives a remarkable decrease of the current carrying capacity. This degraded performance, and the influence of parameters such as B_{min} , B_{max} , and τ still have to be investigated. The results promise a good perspective for switching at 50 Hz.

Figure 4. Current carrying capacity of the gate in a d.c. magnetic field at various frequencies.

Figure 5. Maximum current that can be actually switched with $B_{min}=0$ T, $B_{max}=0.75$ T, and $\tau_1=\tau_2=30$ ms.

References

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