NbTi THERMALLY CONTROLLED SWITCHES FOR SUPERCONDUCTING CONVERTERS WITH OPERATION FREQUENCY UP TO 50 Hz. PART 2: THEORY AND ANALYSIS.

G.B.J. Mulder* O.A. Shevchenko* M.A. Fedorovsky* H.H.J. ten Kate*

* Applied Superconductivity Centre, University of Twente (TN-LT), P.O. Box 217, 7500 AE Enschede, The Netherlands.

* Institute of Electrodynamics, Ukraine Academy of Sciences, Peremoga Prospekt 56, Kiev 57, 252680 Ukraine.

A review is given of several known thermally controlled switches developed for superconducting converters. It shows their rather low frequency of operation (up to a few Hz) which strongly differs from the industrial frequency. This is not only due to the long recovery times of the switches, but also to the fact that the efficiency drops as the frequency increases. To develop switches suitable for 50 Hz, having reasonable efficiency, a theoretical model of the switch is necessary. Such a model is presented here, and illustrated for 50 Hz switches made from NbTi foil.

INTRODUCTION

The superconducting (sc.) switches considered in this paper are the thermally controlled ones intended for fast cyclic operation, to be used for example in sc. power converters. When operating in a sc. convertor, the switches will alternate between the normal and sc. states at a frequency of several Hz. Therefore, the switch should have a short triggering time (time to heat up to the normal state) as well as a short recovery time (time required to cool down to the sc. state).
A thermally controlled switch basically consists of a superconductor which is in good thermal contact with a heating element. The heater is used as a trigger, to to create normal zones in the superconductor, i.e. to open the switch. Conductor and heater are insulated from the coolant by means of an insulation layer. In order to obtain a fast thermal response the switch should have a lay-out similar to that of Fig. 1, where the layers of conductor, heater, and insulation are very thin. Thus, the enthalpy of the switch per unit cooling surface can be minimized. Concerning the thickness d_u of the insulation layer we have to keep in mind that there is an essential contradiction between a short recovery time t_r and high efficiency. On the one hand d_u should be small in order to achieve fast recovery. On the other hand, a small value of d_u means that more power is needed to sustain the resistive state of the switch, leading to an increase of the loss.
According to our model, the leakage loss varies with $1/\sqrt{t_r}$ when changing d_u ceteris paribus, which is illustrated in Fig. 2 with solid lines. The position of these lines depends on the geometry and materials of the switch, in particular on the energy density ρJ_c^2 of the conductor. Figure 2 shows a number of experimental switches known from literature. The boxes indicate the 50 Hz switches that are under development now and described in a separate paper at this conference [1]. Other important parameters are the maximum operating current I_{mx} and voltage V_{mx}, see figure 3. Note that their product $V_{mx}I_{mx}$ is a measure for the power that can be rectified.

Table 1 Data of 9 thermally controlled switches shown in Figs. 2 and 3.

Number	1	2	3	4	5	6	7	8	9
Reference	[2]	[3]	[4]	[4]	[4]	[4]	[5]	[6]	[7]
I_{mx} [A]	9000	26000	180	1250	1800	1400	1000	60000	100
I_p [A]	7	16	0.13	5.3	4.0	4.0	3.2	290	0.42
R_{mx} [Ω]	0.002	0.007	113	0.84	0.84	0.84	1.5	$3\cdot10^{-5}$	0.18
t_r [s]	≅ 2	≅ 1	0.4	0.16	0.08	0.08	0.12	0.35	0.01
T_p [K]	11.7	11.7	11.7	11.7	12.2	12.2	12.2	11.3	11.5
E_{act} [J]	0.3	?	?	0.5	0.3	0.2	0.06	2	0.0004
f [Hz]	0.1	0.1	0.5	1	2	2	3	0.4	5

OPERATION

During cyclic operation of the switch, four stages can be distinguished:

1) **Triggering.** The switch is opened by supplying a pulse to the heater. The required energy E_{act} of this pulse is minimized by means of a heater with special shape. It touches the conductor locally at N equidistant points.
2) **Normal state.** An applied voltage V_{sw} over the switch will cause propagation of the N normal spots. If V_{sw} varies sufficiently slowly, a thermal equilibrium will be reached for which the leakage current is constant, namely equal to I_p the minimum propagation current of the conductor [4]. The purpose of triggering N spots is to reach this equilibrium quickly using collective growth or shrinking of the normal zones. An ideal I-V curve in the steady case is shown in Fig. 4. Of course, V_{sw} should not exceed V_{mx} because then the recovery time would increase drastically.
3) **Recovery.** If the applied voltage V_{sw} is sufficiently low (several mV), the normal zones cannot be sustained and the switch recovers. Recovery is the thermal process where the superconductor cools down to below T_c, mainly due to the heat removal in a direction transverse to the sc. layer (y-direction).
4) **Superconducting state.** In sc. state the switch has to carry a relatively large current. The maximum current I_{mx} generally depends on the current rate and on the time after recovery.

THE MODEL

We will assume a uniform temperature T over the cross-section of the conductor since the insulation material has a poor thermal conductivity compared to NbTi. A further assumption is that the enthalpy of conductor and heater dominates that of the insulation layer. So, the heat capacity of the insulation layer will be neglected, in which case the temperature of the conductor is governed by

$$c(T)\frac{\partial T}{\partial t} = p(T) - \frac{q_y(T)}{d_y} - \frac{\partial}{\partial x}\left(-\lambda_x(T)\frac{\partial T}{\partial x}\right) \quad , \tag{1}$$

with p(T) the heat production, $q_y(T)$ the heat flux via the insulation, d_y the thickness of the conductor layer i.e. its cross-section divided by its cooling perimeter, and $\partial_x(\lambda\partial_x T)$ the cooling in x-direction. The volumetric specific heat c(T) of the conductor (corrected for the presence of heater and insulation) is calculated as

$$c(T) = c_0+c_1T+c_2T^2+c_3T^3 \qquad \text{where } c_0 \text{ to } c_3 \text{ are empirical constants.} \tag{2}$$

Similarly, we use empirical fits for the conductivities:

$$\lambda_y(T) = c_{0y} + c_{1y}T \qquad \text{for the insulation and} \tag{3}$$

$$\lambda_x(T) = c_{0x} + c_{1x}T \qquad \text{for the conductor.} \tag{4}$$

In the insulation layer the temperature drops from T to T_e. The resulting heat flux $q_y(T)$ is approximated using the temperature profile for stationary heat flow, i.e.

$$q_y(T) = \frac{1}{d_u}\int_{T_e}^{T}\lambda_y(T)dT = \frac{c_{0y}}{d_u}(T-T_e) + \frac{c_{1y}}{2d_u}(T^2-T_e^2) \ . \tag{5}$$

Numerical integration of (1) to (5) gives a realistic simulation of thermal processes in the switch, including the growth and shrinking of normal zones. Such an analysis is beyond the scope of the paper. Instead we will focus on simpler cases which are important and analytically solvable.

Transient behavior of the normal zones. Consider the middle part of the normal zone, i.e. the hottest part, initiated by means of the heater. In this region $\partial_x(\lambda_x\partial_x T)=0$ and the power p(T) is taken constant. The equations (1) to (5) in this case reduce to

$$\frac{dT}{dt}\sum_{i=0}^{3} c_iT^i = A-BT-CT^2 \quad \text{with } A=p+BT_e+CT_e^2,\ B=\frac{c_{0y}}{d_ud_y} \text{ and } C=\frac{c_{1y}}{2d_ud_y} \ , \tag{6}$$

which can be integrated by separation of variables giving T(t) implicitly:

$$t = \int_{T(0)}^{T(t)} \frac{c_0+c_1T+c_2T^2+c_3T^3}{A-BT-CT^2}\,dT \ . \tag{7}$$

Note that (7) is analytically solvable. Depending on p, it describes the heating during triggering stage as well as the cooling during recovery. From (7) the recovery and triggering times can be calculated as well as the energies associated with it.

Stationary normal state. In this case $c(T)\partial_t T=0$. Solving (1) to (5) we find a unique current density j_p for which stationary normal zones can co-exist with sc. regions. In this minimum propagation state, the temperature of the normal zones is T_p, which is about $1.3T_c$ for NbTi and rather independent of materials or geometry, see Table 1. Assuming T_p is known, for example 12 K, then j_p can be computed using $\partial_x(\lambda_x\partial_x T)=0$ and $p=\rho j_p^2$ in the middle of a normal zone. One obtains

$$j_p = \sqrt{(A-BT_p-CT_p^{\,2})/\rho}. \tag{8}$$

RESULTS FOR SWITCHES WITH NbTi FOIL AND KAPTON INSULATION

To illustrate the above model we consider the practical case of thermally controlled switches with NbTi foil and Kapton insulation (both about 10 μm thick) using T_p=12 K, T_e=4.5 K and T_c=9.4 K. Fig. 5 shows the measured and calculated recovery process as a versus reduced time t/t_0. The time constant t_0 of the gate is defined $2d_u d_y c_3 T_c^2/c_{1y}$. As the temperature drops during recovery (line 3) the maximum allowable current I_{mx} increases (line 4). Line 4.1 is found by calculating the temperature from (7) using p=0 and assuming a linear $I_c(T)$ dependence, while lines 4.2, 4.2, 4.4 correspond to measurements in [5], [6], [1] respectively. Line 1 is the expected maximum current, based on dynamic stability, if the gate would already be at T_e.
When rectifying a rectangular voltage, a stationary situation with constant R_{sw} will rapidly occurs after triggering the switch, especially if N is large. The situation is more complex when rectifying sinusoidal signals because the normal zones will grow or shrink as the voltage changes. Therefore, the leakage current and maximum temperature make deviations around the values T_p and I_p. The deviations depend on N, the dynamic properties of the switch and dV_{sw}/dt. This process is illustrated in Fig. 6, which was calculated by numerically solving (1). The figure shows that the ohmic loss in the gate is given by $\overline{I}_p\int V_{sw}dt$, where $\overline{I}_p$ is an effective leakage current slightly higher than the I_p under stationary conditions. The figure also shows the automatic recovery of the switch as the 50 Hz sinusoidal voltage goes through zero.

CONCLUSIONS

A model is presented describing the processes in thermally controlled sc. switches. It enables calculation of relevant thermophysical characteristics of the switch, like minimum propagation current, evolution of the superconductor temperature, trigger and recovery times and efficiency. Such a detailed analysis of the switch is particularly useful for low-loss 50 Hz operation. The results predict the possiblity of thermally controlled sc. power converters operating at 50 Hz with an efficiency of about 98 %.

REFERENCES

1 Shevchenko, O.A., Mulder, G.B.J., Markovsky, N.V., ten Kate, H.H.J., NbTi foil thermally controlled switches for superconducting converters with operation frequency up to 50 Hz. Part 1: experiment, This conference

2 ten Kate H.H.J., Bunk P.B., Steffens H.A., van de Klundert L.J.M., A thermally switched sc. 9 kA rectifier flux pump, IEEE Trans. on Magn. (1981) 17 2076-2079

3 ten Kate, H.H.J., Holtslag, A.H.M., Knoben, J., Steffens, H.A., van de Klundert, L.J.M., Status report of the 25 kA, 1.5 kW thermally switched superconducting rectifier. Transformer and switches, IEEE Trans. on Magn. (1983) 19 1059-1062

4 Mulder, G.B.J., ter Avest, D., ten Kate, H.H.J., Krooshoop H.J.G., and van de Klundert, L.J.M., Experimental results of thermally controlled superconducting switches for high frequency operation, IEEE Trans. on Magn. (1988) 24 907-910

5 Mulder, G.B.J., Increasing the operating frequency of sc. rectifiers, PhD Thesis University of Twente, Enschede, The Netherlands (1988)

6 Mulder, G.B.J., ten Kate, H.H.J., Krooshoop, H.J.G. and van de Klundert, L.J.M., Development of a thermally switched superconducting rectifier for 100 kA, IEEE Trans. on Magn., (1991) 27 2333-2336.

7 Chernavsky Yu.P., Malkovsky V.I., Skobarikhin Yu.V., Electro- and thermophysical characteristics of thermally controlled cryotrons, Cryogenics (1992) 32 309-314

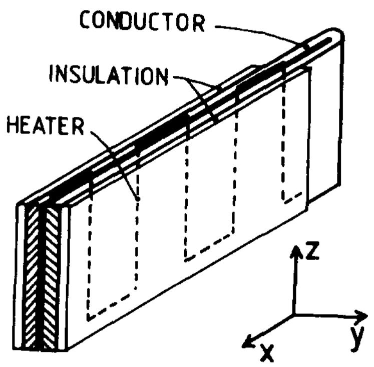

Figure 1 Schematic layout of a switch with bifilarly folded tape conductor.

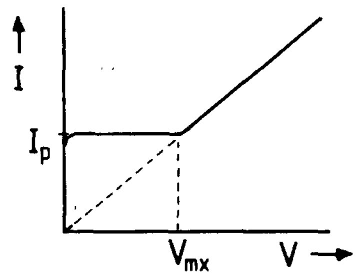

Figure 4 Voltage-current curve of the switch in stationary resistive state.

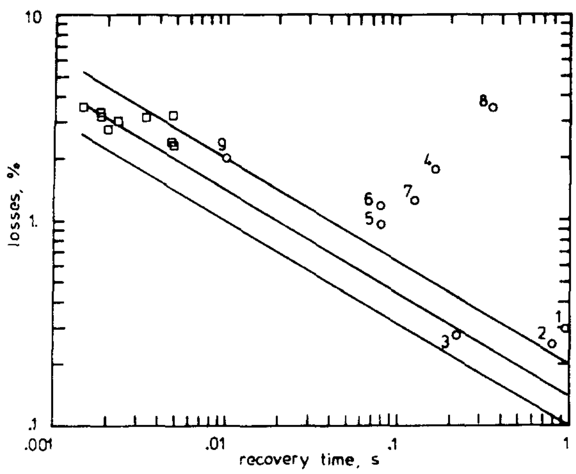

Figure 2 Loss versus recovery time:
O switches from literature, Table 1;
□ switches being developed now [1];
—— theoretically, when changing d_u.

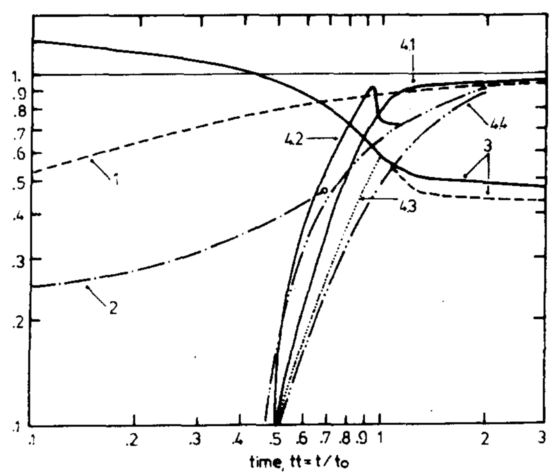

Figure 5 Recovery process:
1) Dynamic stability criterion: I_{mx}/I_c;
2) Scaled activation energy;
3) Scaled sc. temperature T/T_c;
4) Scaled maximum current I_{mx}/I_c.

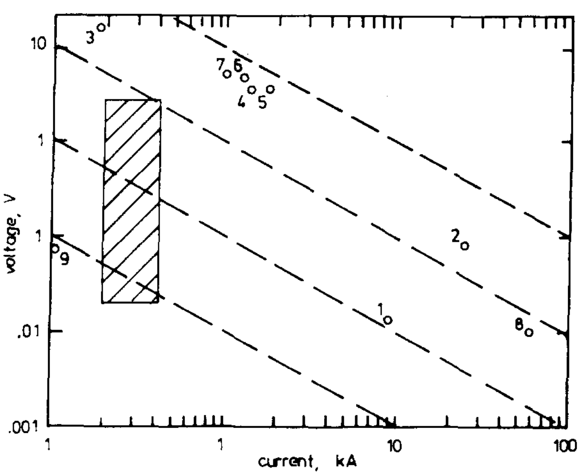

Figure 3 Operating range I_{mx} and V_{mx}:
O switches described in Table 1;
▨ investigated regime in [1];
– – – power of .01, .1, 1 and 10 kW.

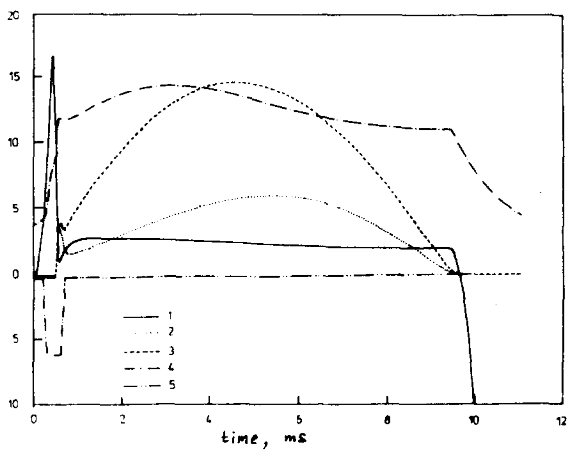

Figure 6 Rectifying process for 50 Hz sinusoidal signal: 1) current [A]; 2) resistance [Ω]; 3) voltage [V]; 4) temperature [K]; 5) heater signal.