NbTi FOIL THERMALLY CONTROLLED SWITCHES FOR SUPERCONDUCTING CONVERTERS WITH OPERATION FREQUENCY UP TO 50 HZ. PART 1: EXPERIMENT.

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The increase of the operation frequency of superconducting converters up to 50 Hz opens new ways to improve their parameters. Thermally controlled switches using NbTi foil are able to operate at industrial frequency with reasonable efficiency and dynamic parameters. Such switches have been developed and tested. The paper presents experimental results of static and dynamic behavior of the switches. The rectification mode was tested with different shapes of the applied voltage, with currents from 150 to 450 A, voltages from 10 mV to 2.5 V and recovery times between 1 and 10 ms. The switches presented here have experimentally demonstrated superior dynamic parameters at higher efficiency than the ones reported in literature up to now.

INTRODUCTION

Thermally or magnetically controlled repetitive switches are usually applied in superconducting (SC) converters for ramping up and down and/or stabilize the current in inductive loads at helium temperatures [1]. Operation of such switches is based on the controlled phase transition between the SC and normal states. Due to very low resistance in the SC and normal states compared to usual semiconducting devices (such as diodes, etc.) they can provide a more efficient operation at high current low voltage rectification and invertion combined with long energy storage time which usually takes place during the operation of SC magnets. Advantages and disadvantages of these types of SC switches are known [2]. In our opinion, a common disadvantage of both types so far was the absence of a simple, reliable and efficient switch able to operate at the industrial frequency and using an applied voltage with wide amplitude range. To realize such a switch means substantial simplification of the SC converter construction and operation. For this purpose we developed some thermally controlled SC switches based on NbTi foil, which satisfy all necessary requirements.

APPARATUS

Circuit: The simplified electrical scheme of the circuit used to investigate the switches is presented in Fig. 1. It consists of two power units: (1) a high voltage, low current unit; (2) a high current, low voltage unit; (3) control unit; (4) cryostat with liquid helium; SC transformer (SCT); switches K1 and K2; three low inductive high current leads (C,D,E), etc.
Unit 1 converts the frequency, amplitude and shape of the net voltage to appropriate values; unit 2 enables direct measurement of the current in switches and load (by means of shunts). Depending on the type of experiment it includes also voltage or current supply and/or variable active and inductive loads. Unit 3 supplies the heaters of the switches by control voltages of appropriate amplitude and length. The SCT with cold iron core and two secondary semi-windings generates the secondary currents up to 600 A at voltages up to 1 V (at each semi-winding) in the frequency range of 10 to 500 Hz.
A PC in combination with DASH-16 card is used for data acquisition, signal analysis and storage of experimental information.
Layout: Thermally controlled switches all using planar technology were investigated. The longitudinal cross-section of such a switch is presented in Fig. 2. The upper

and lower (not shown) halves of the cross-section are symmetrical, except for the power current direction (shown by arrow). The switch consists of a heater layer 1 sandwiched by electrical insulation layers 2, bifilar NbTi foil layers 3, thermal insulation layers 4, heat conducting plates 5 (expanded by fins to enlarge the external surfaces in case of direct cooling by liquid or gas) and some interface layers filled with impregnation. Additional self-field shields layers may be placed between layers 4 and 5 (see TS 6 in Table 1). Also, external field shields were placed at the outer sides of plates 5.

Heater: Discrete heaters in the direction of switch power current have been prepared from high resistivity material using foil and film technology. We choose important heater sizes h_1 about 4.5 mm, h_2=.3-.45 mm for different switches as reasonable optimum values between theoretical requirements and technological possibilities for industrial frequency operation.

Gate conductor: The gate consists of commercially available NbTi foil produced in Russia, having 8 and 12 µm thicknesses with 50% Nb (NT) and 22% Nb (TN) content respectively. Materials with different heat and mechanical treatments have been used after proper preparation as gate conductor in all investigated switches.

Thermal insulation layer: 12.5 µm Kapton has been tested as thermal insulation layers for all investigated switches .

MEASUREMENTS

The switch investigation procedure has included the following measurements:
gate and heater resistances vs temperature; static current-voltage characteristics in resistive and normal state activated by a heater pulse; gate DC critical current in SC state (at 4.2 K and zero external magnetic field); gate maximum current and self-inductance in AC mode and rectangular as well as sinusoidal (SIN) applied voltage in the frequency range 10-500 Hz; dependence of the total velocity of normal zones propagation and shrinking vs time at constant and rectangular (with pauses) current; i- dynamic parameters of the switch in rectification mode at rectangular and SIN applied voltage (power current, gate and heater voltages vs time, and maximum gate current I_{mx}, leakage current, voltage drop, heater power and so on); ii- for pairs of switches (single phase full-wave SC rectifier mode with disconnected output, or short-circuited output, or active load) measurements of leakage currents, maximum gate voltage and maximum gate currents; iii- the modes i, ii with SIN applied voltage and variable frequency beween 10 and 500 Hz measurements of maximum SC and leakage currents.

RESULTS AND DISCUSSION

Main parameters of the switches are summarized in Table 1. Measured values of gate activation time typically lie between .35 and .5 ms, transition time from initial value of leakage current to minimum propagation one (stationary value) was about 1.5 ms. The switch recovery time strongly depends on the selected level of maximum current recovery, so the switch time constant (see [3]) is the best parameter describing this process.

Figure 3 shows TS 8 static current-voltage characteristic. After triggering the heater, voltage is applied to the gate and changed sufficiently slowly to guarantee thermal equilibrium. It clearly shows the constant leakage current, equal to minimum propagation current, 1.8 A in this case. At maximum voltage, 2 V in this case, the whole gate length is normal.

Figure 4 shows TS 1 recovery behavior in 50 Hz rectification mode. In this mode switch is triggered once per period and then a bipolar rectangular voltage (with pauses for switch recovery and triggering) is applied to the SCT primary winding. During part of the cycle the switch is in normal state, its resistance dominates in the SCT secondary circuit, so the voltage drop (1.7 V in this case), is close to voltage generated by the SCT and the leakage current in the gate is small (2 A). Then, the applied voltage becomes zero and some time (.6 ms) is necessary for the gate to cool below critical temperature. From this moment the switch is able to carry current without active resistance, so the induced current during time when secondary voltage is generated again is determined by other circuit parameters. Selecting inductance and resistance of the unit 2 (see Fig. 1), one can get current ramping during switch SC state close to switch maximum current recovery (real voltage sign is opposite to the one shown in Fig.4).

Figure 5 shows similar results obtained for a pair of switches (TS 4, 5) at SIN applied voltage. Figure 6 illustrates the measured maximum current of switch TS 5 versus operational frequency in SC state and rectification mode iii.

CONCLUSION

Using NbTi foil as gate material it is possible to increase the operation frequency of thermally controlled switches up to 50 Hz at acceptable level of switch efficiency and dynamic characteristics. Initial activation of a large amount of short normal zones (up to 200 m^{-1} in our experiments) results in a switch with fast relaxation of the gate resistance to the stationary value thereby able to operate efficiently at any type of applied voltage, i.e. sinusoidal as well as rectangular. DC current densities up to 10 GA/m^2 and specific power $j^2\rho$ up to 7×10^{13} W/m^3 were achieved experimentally , which gives good prospects for further improvements of the switch characteristics.

REFERENCES

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3 Mulder G.B.J., Shevchenko O.A., Fedorovsky M.A. and ten Kate H.H.J., NbTi thermally controlled switches for superconducting converters with operation frequency up to 50 Hz. Part II: theory and analysis, This conference paper.

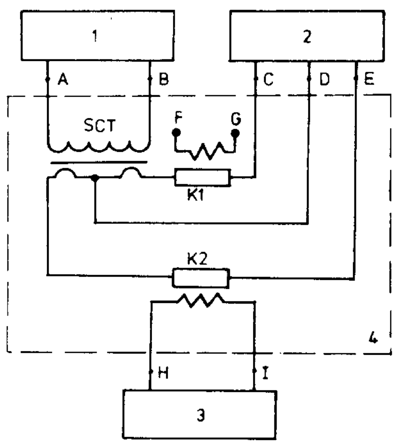

Figure 1 Circuits representation of experimental facility for switches tests.

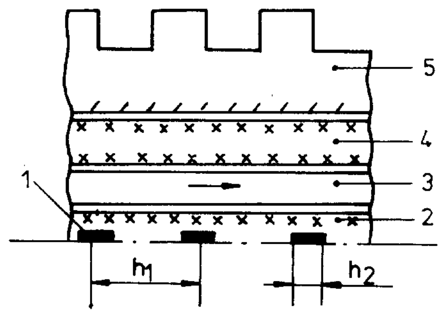

Figure 2 Longitudinal cross-section view of thermally controlled switch

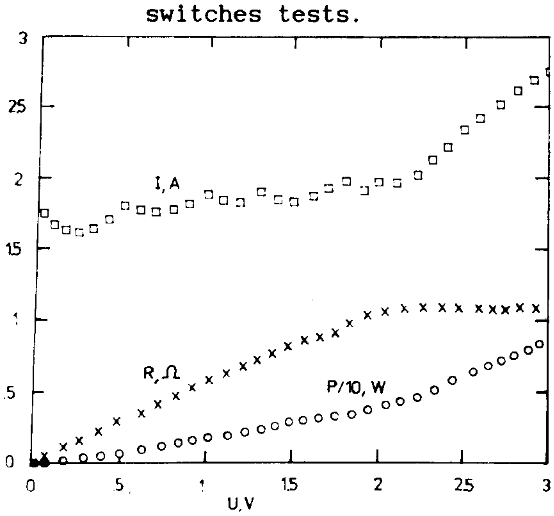

Figure 3 Switch TS 8 stationary current to voltage characteristic in resistive and normal state (gate resistance R and power dissipation P are also shown

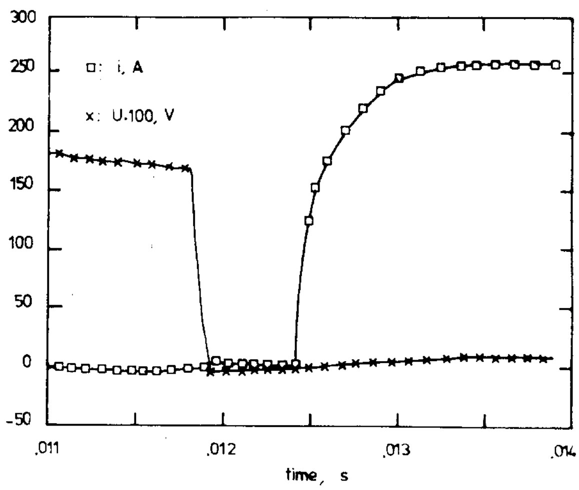

Figure 4 Switch TS 1 rectification mode (recovery fragment is shown), I, U-gate current and voltage drop respectively

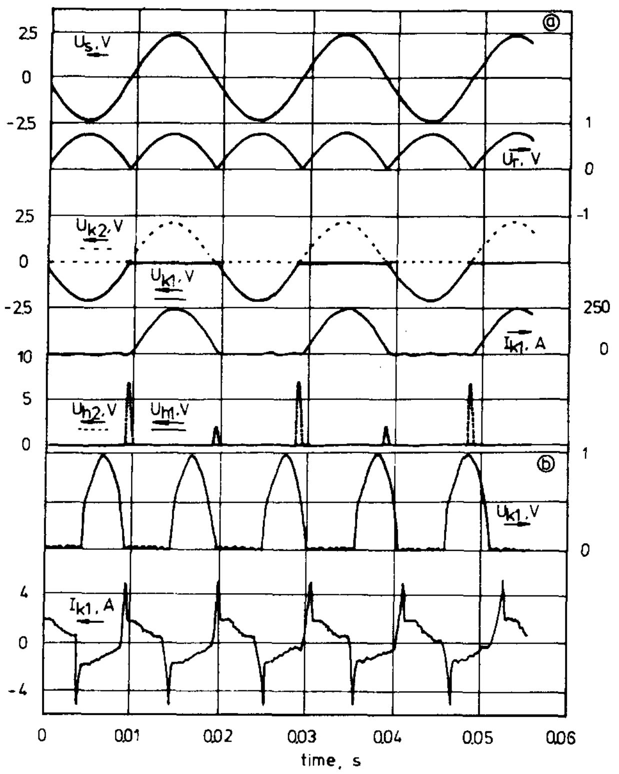

Figure 5 Dependence vs time of transformer voltage U_s; warm load resistor U_r and TS4 (K2), TS5 (K1) gate ($U_{k1,2}$) and heater ($U_{y1,2}$) voltage drops; current (I_{k1}); a-50 Hz , b-100 Hz operation frequency

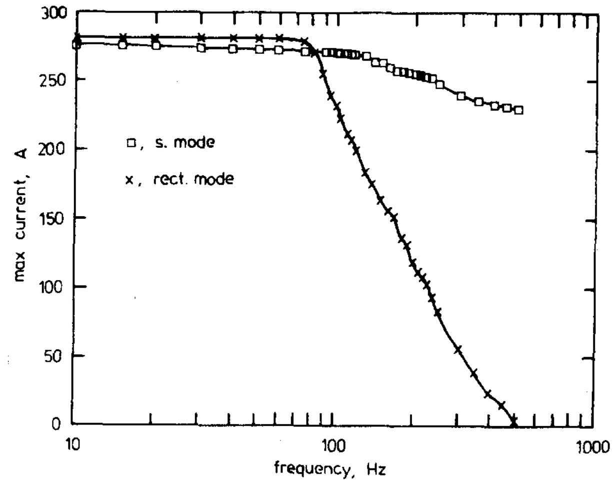

Figure 6 Maximum current of TS 5 versus operational frequency at sinusoidal applied voltage in SC state (boxes) and in rectification mode (crosses)

Table 1 Summary of data and results for Nb-Ti foil switches

Switch parameter\number	1	2	3	4	5	6	7	8	9
conductor material code	NT	NT	TN	TN	NT	NT	NT	TN	NT
active length, m	.06	.1	.1	.1	.1	.1	.1	.1	.1
Cross-section area, $\times 10^{-8} m^2$	4	3.8	6	6	3.4	3.3	3.4	6	6.4
Filling coefficient	.29	.25	.35	.35	.25	.20	.25	.36	.24
Power joints	+	+	#	+	+	+	+	+	+
Gate static parameter:									
Max off-resistance, Ohm	.82	1.4	1.2	1.1	1.55	1.63	1.6	1.1	.96
Min off-resistance, Ohm	.012	.014	.013	.013	.01	.013	.014	.013	.012
Min propagation current, A	2.05	1.4	1.5	1.5	1.4	1.4	1.35	1.75	2.1
Critical current, A	386	336	546	560	280	306	280	360	440
Gate dynamic parameter:									
*Max si-current at 100 Hz, A	325	255	190	252	266	290	272	250	380
*Max re-current at 60 Hz, A	385	330	180	320	270	305	280	360	440
time constant, ms	1.3	1.7	4	4	1.5	1.9	1.5	2.9	2.8
Heater:									
resistance at 4.2K, Ohm	5.5	14.9	13.0	14.4	10.9	10.7	10.9	14.4	11.7
Min activation voltage, V	1.7	3	4	4.2	2.6	2.5	2.6	4.5	3.2

si-sinusoidal in SC state , re-rectified currents (at sinusoidal applied voltage) ;
+ soldered, # welded